



Ices of the Universe

Murthy S. Gudipati

*Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109*



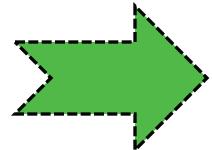
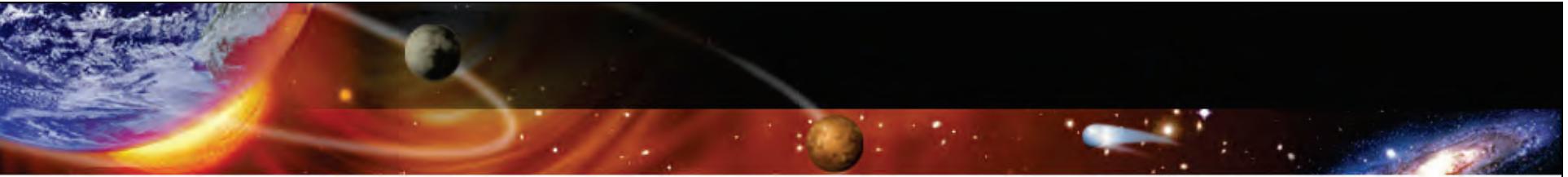
JPL Science 101 Jan 24, 2011



Outline

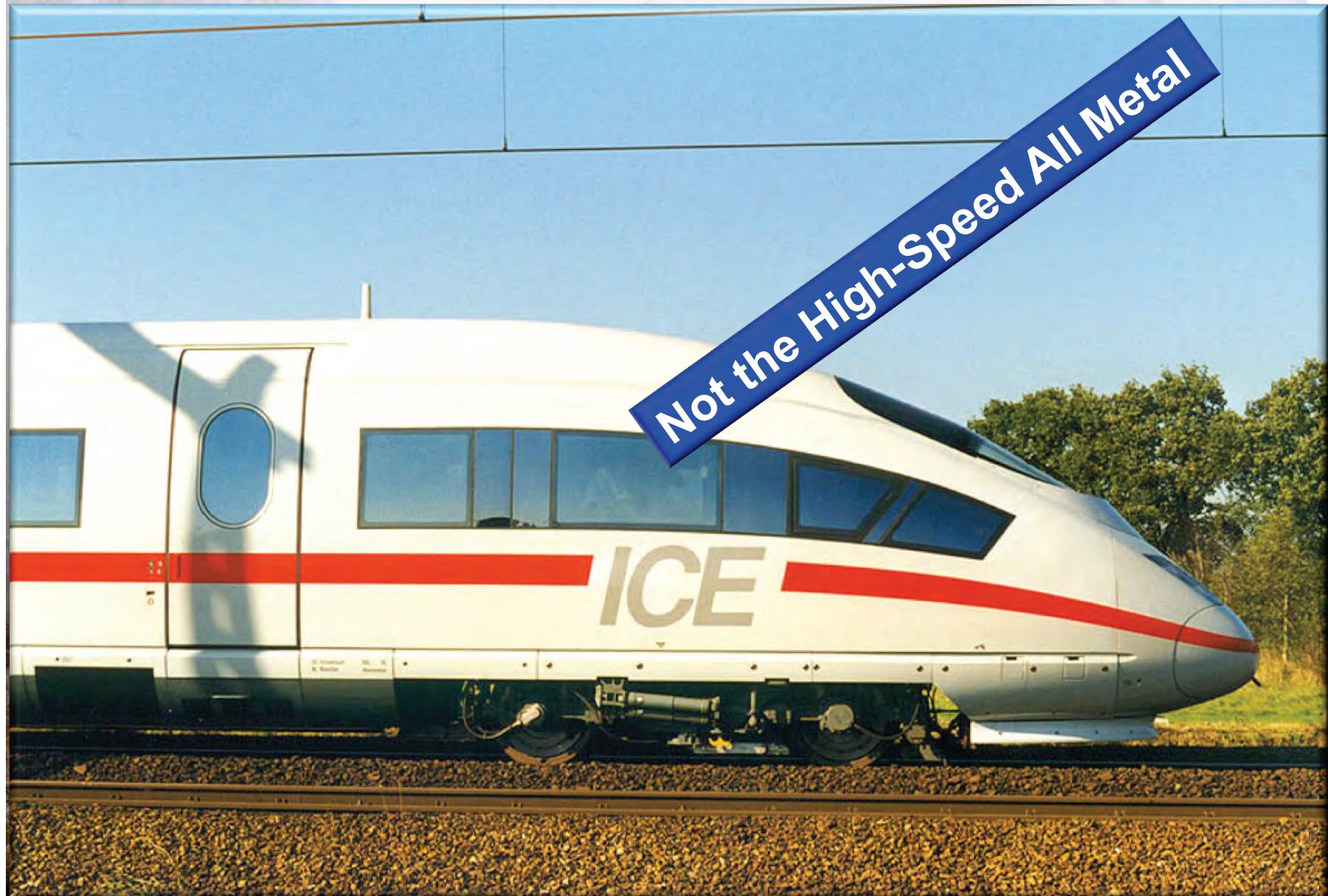
- Ice: Definition
- Ice: Source of Water and Life? - Motivation
- Ice Spectroscopy Lab (ISL) @ JPL
- New Science Results from ISL
- Implications
- Some outstanding issues
- Future

Do not hesitate to ask questions!



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Ice: Not the Inter City Express (*ICE*)



Dictionary Definition of ICE

¹**ice**



noun, often attributive

\'īs\

Definition of ICE

1 a : frozen water

b : a sheet or stretch of ice



m-w.com

Ice: Frozen Water

This talk focuses on H₂O (Water) Ice in the Universe

Other Common Solar System Ices:

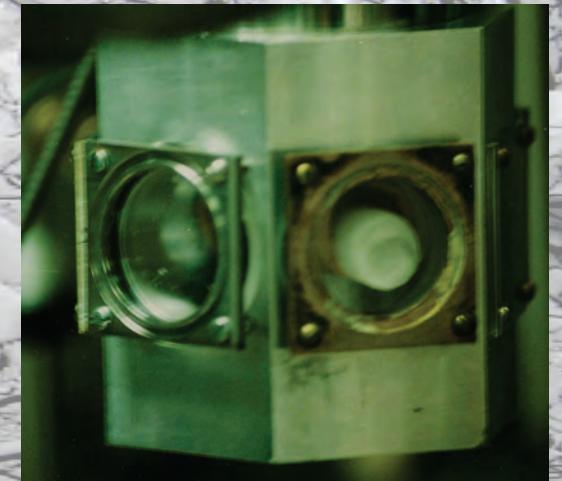
Methane, Methanol, Ammonia, Carbon Dioxide, Nitrogen, etc.



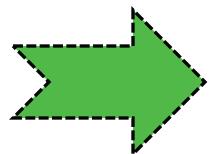
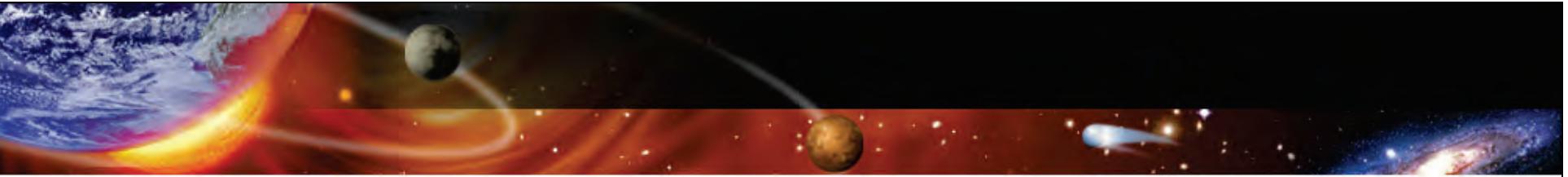
Nitrogen Ice on
Triton (Neptune's Moon),
Pluto, and beyond



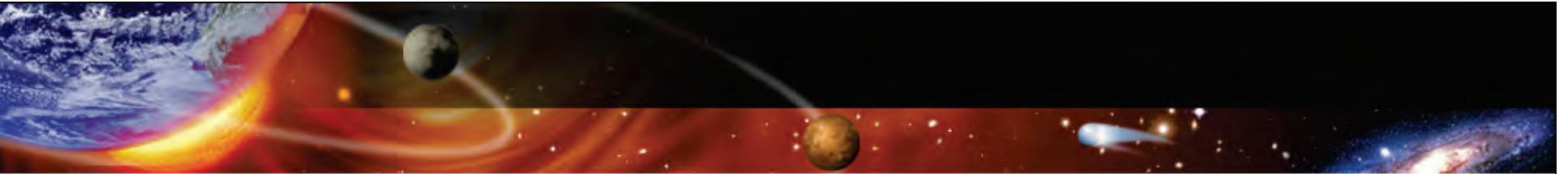
Dry Ice
(Carbon Dioxide Ice)
Found on Mars;
Outer Solar System



Argon Ice in Lab
(Murthy Gudipati 1987
UT-Austin); May exist
in Cold Space, but
difficult to detect!



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Origin (s) of Life & Comets

Water – Essential for Life (as we know it now)



- ❖ Water
- ❖ Organic Matter (C,H,N,O,P,S)
- ❖ Minerals
- ❖ Light/Energy



Origin (s) of Life and Comets

The Three working postulates for the origin of life on Earth:

Miller's (Miller & Urey) Experiment:
Lightning induced formation of amino acids.

Exogenisis:

Comet impacts brought water and organics to the Earth that resulted in biogenesis.

Hydrothermal Vents Catalysis (Mike Russell):
Oceanbed high-temperature hydrothermal vents catalyzing conversion of CO₂ to biomolecules.

The Origin(s) of Life – Role of Comets

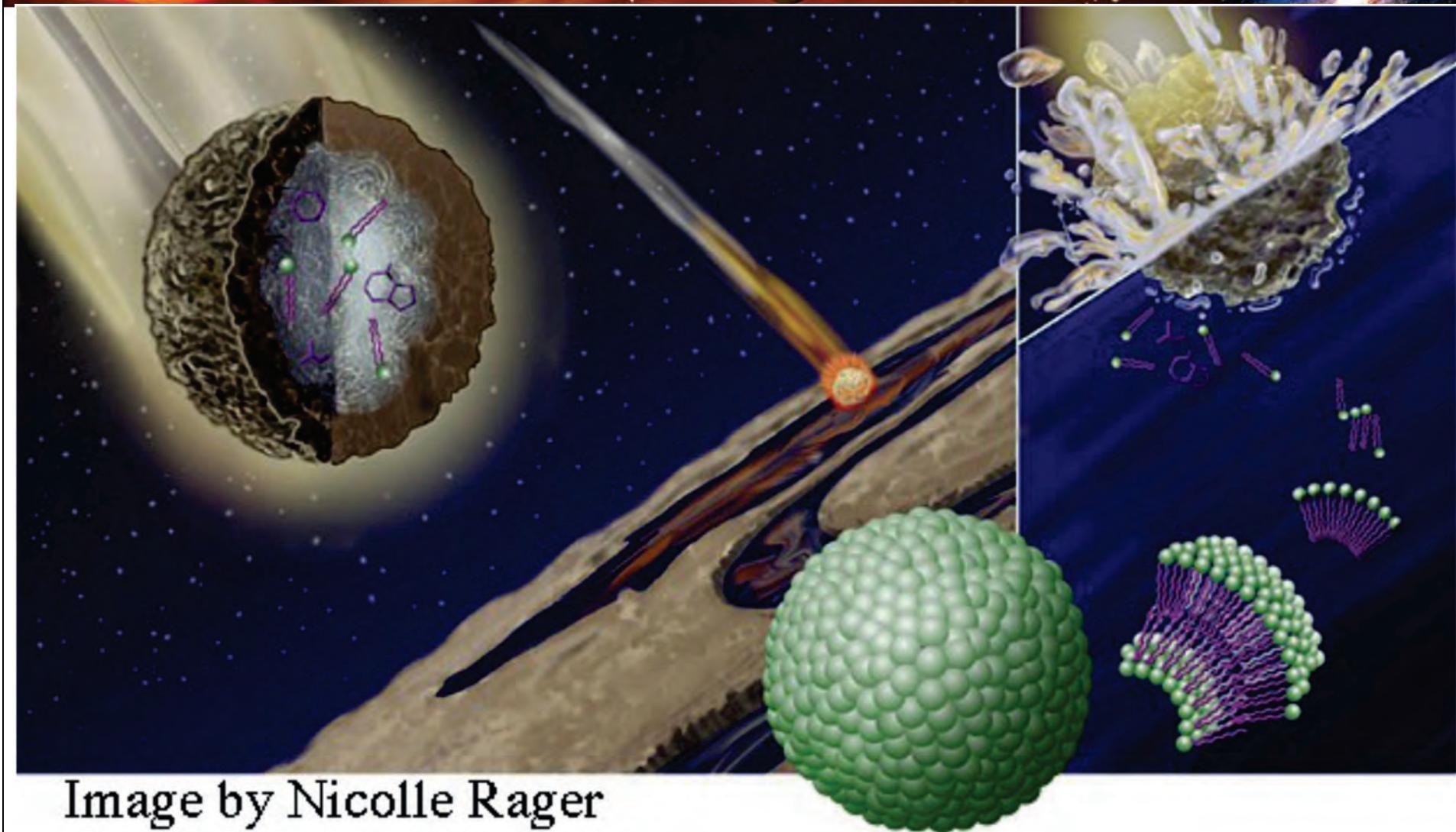
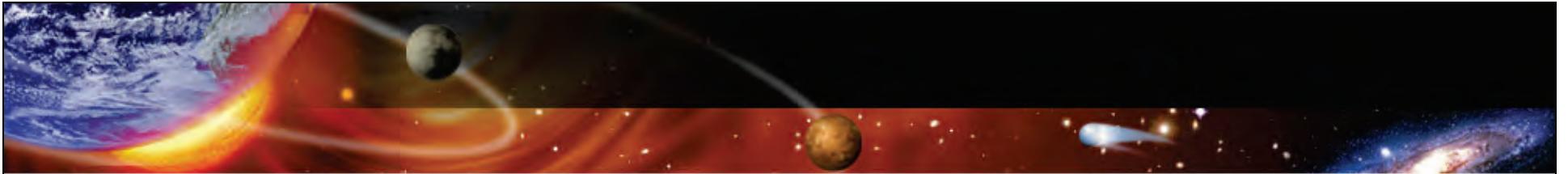


Image by Nicolle Rager

Did Organics Survive Comet Entry and Impacts on Earth?
Do we fully understand Comets? (Deep Impact, Epoxi, Rosetta)



Solar System & Astrobiology



Are We Alone in our Solar System (Galaxy/Universe)?

One of the key goals of
NASA's Astrobiology Institute is:

What are the Potentially
“Habitable” Places in Our Solar System?

Potentially Habitable Places Are:

Mars

Europa

Titan

???

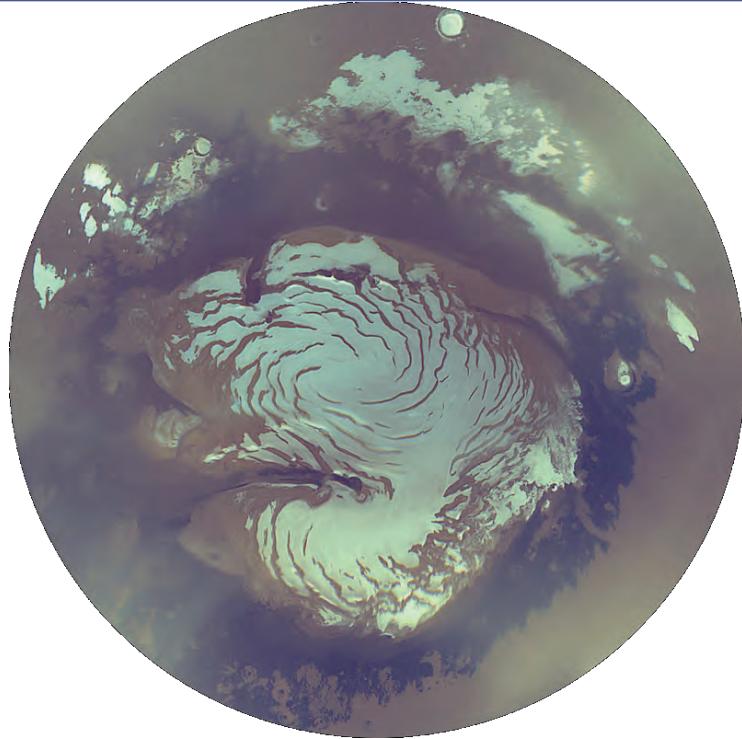
Is there life elsewhere? If yes, how can we detect it?
(Galileo, Cassini, future EJSM, future TSSM, MSL, ...)

Ice on Mars - Yes; Organics ??

Phoenix Mission
revealed ice
under Martian soil



A view of the north polar ice cap on Mars taken by NASA's Mars Reconnaissance Orbiter (MRO). Mars Science Lab (MSL) will probe chemical composition of Martian Surface.

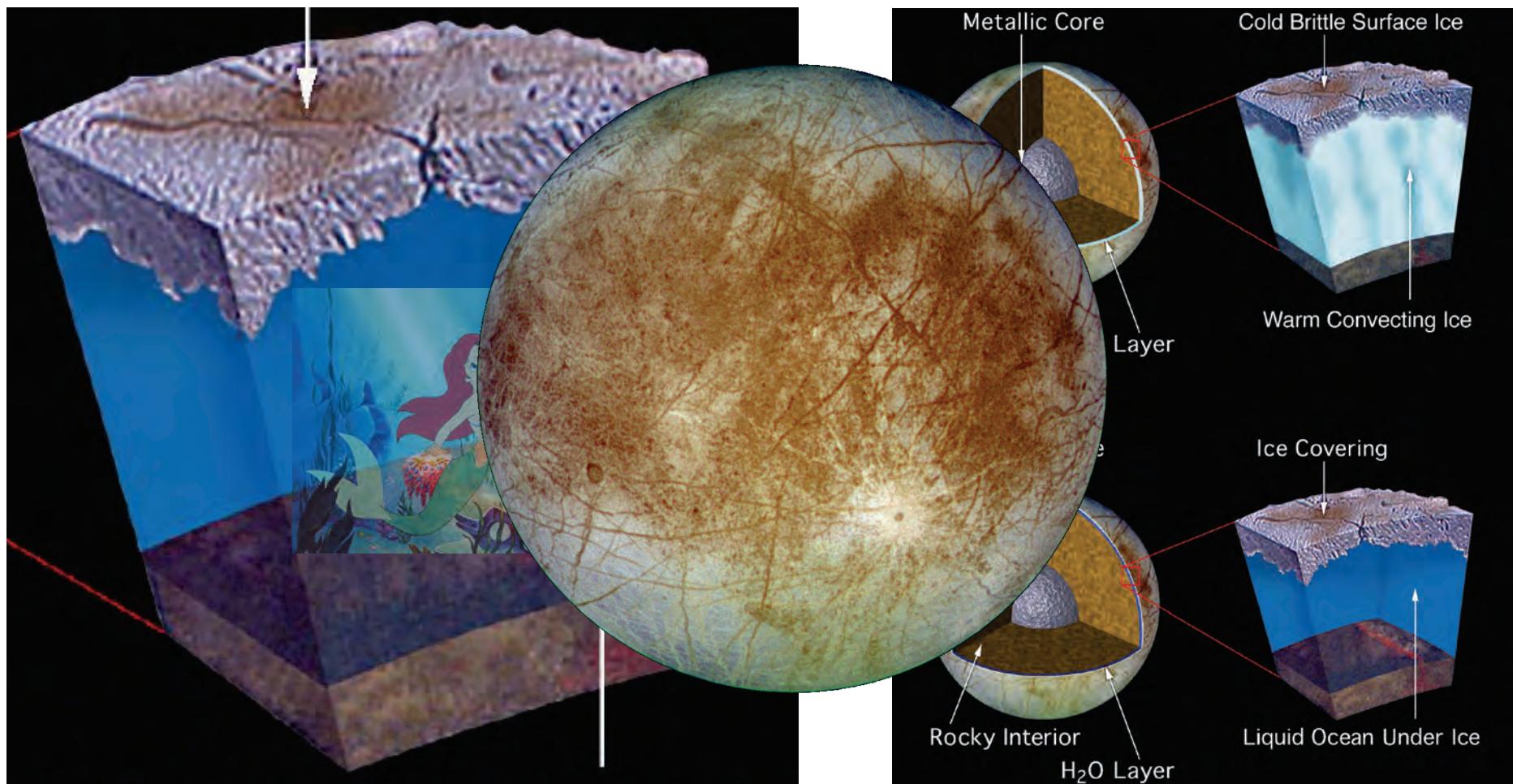


Can we detect organics/biomolecules/life on Mars?
Was/is there life on Mars? Can there be life in the future?
Is Mars habitable?

(Spirit, Opportunity, Curiosity (MSL), Phoenix, MRO, and many more)

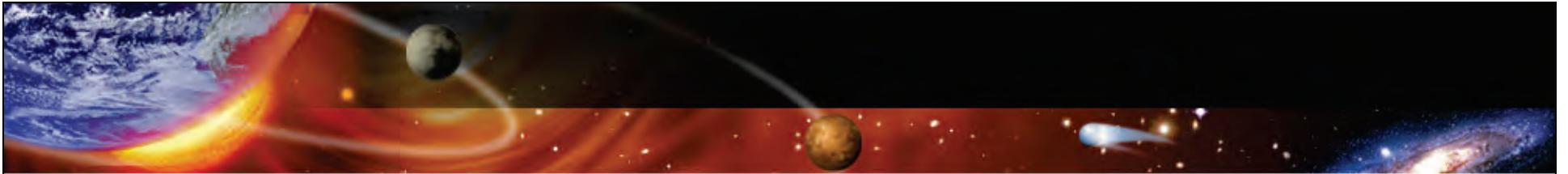
Habitability in Europa? How to detect?

Magnetometer Data from Galileo Mission and Modeling
Infer Potential Subsurface Oceans on Europa that could be Habitable!
Future EJSM (JEO) Mission will take a close look into the Oceans



Saturn's Moon Titan as a Prebiotic System?

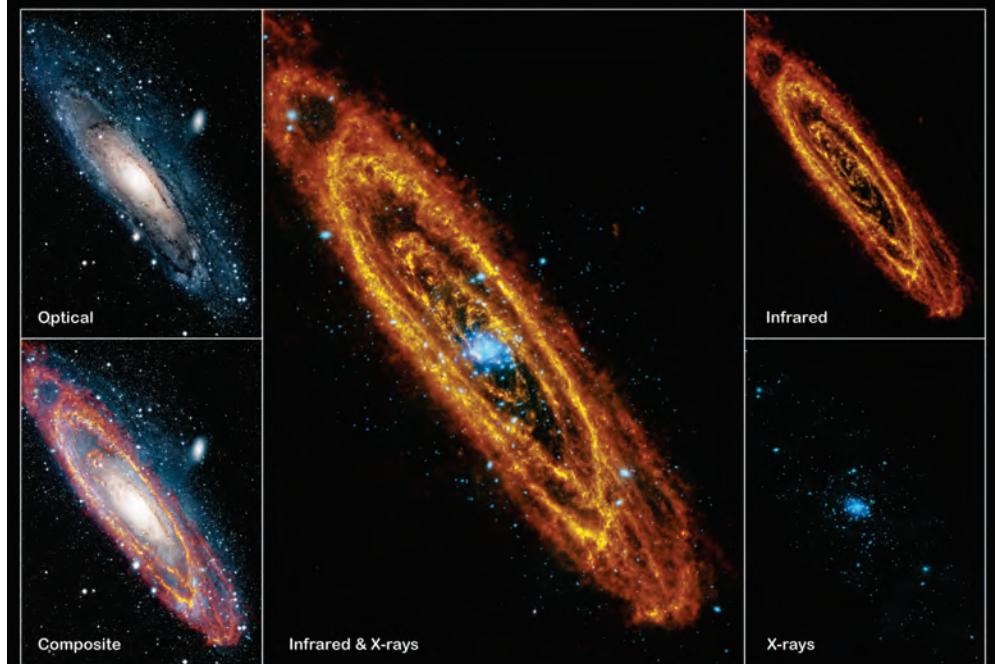
Titan – The Organic-Rich Moon with Ice on its Surface
Can Molecules of Life on Surface be transported into potentially
habitable Subsurface? Future TSSM Mission will have answers



Interstellar Matter & Evolution of Stars

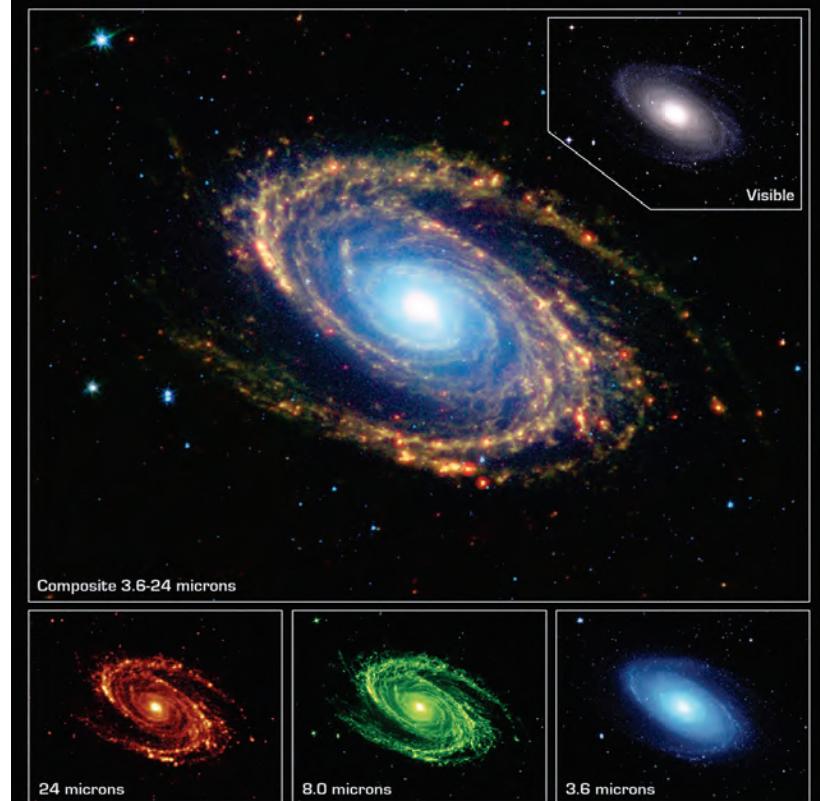
Cold Places in the Galaxies – Reservoirs of Ice

January 5, 2011 -The Andromeda Galaxy



Credits: infrared: ESA/Herschel/PACS/SPIRE/J. Fritz, U. Gent; X-ray: ESA/XMM-Newton/EPIC/W. Pietsch, MPE; optical: R. Gendler

Spitzer Mission as well as Herschel/Planck Missions reveal new regions in galaxies that contain cold icy-dust.



Spiral Galaxy M81

NASA / JPL-Caltech / K. Gordon (University of Arizona), S. Willner (Harvard-Smithsonian CfA)

Spitzer Space Telescope • MIPS • IRAC

Inset: visible light (NOAO)

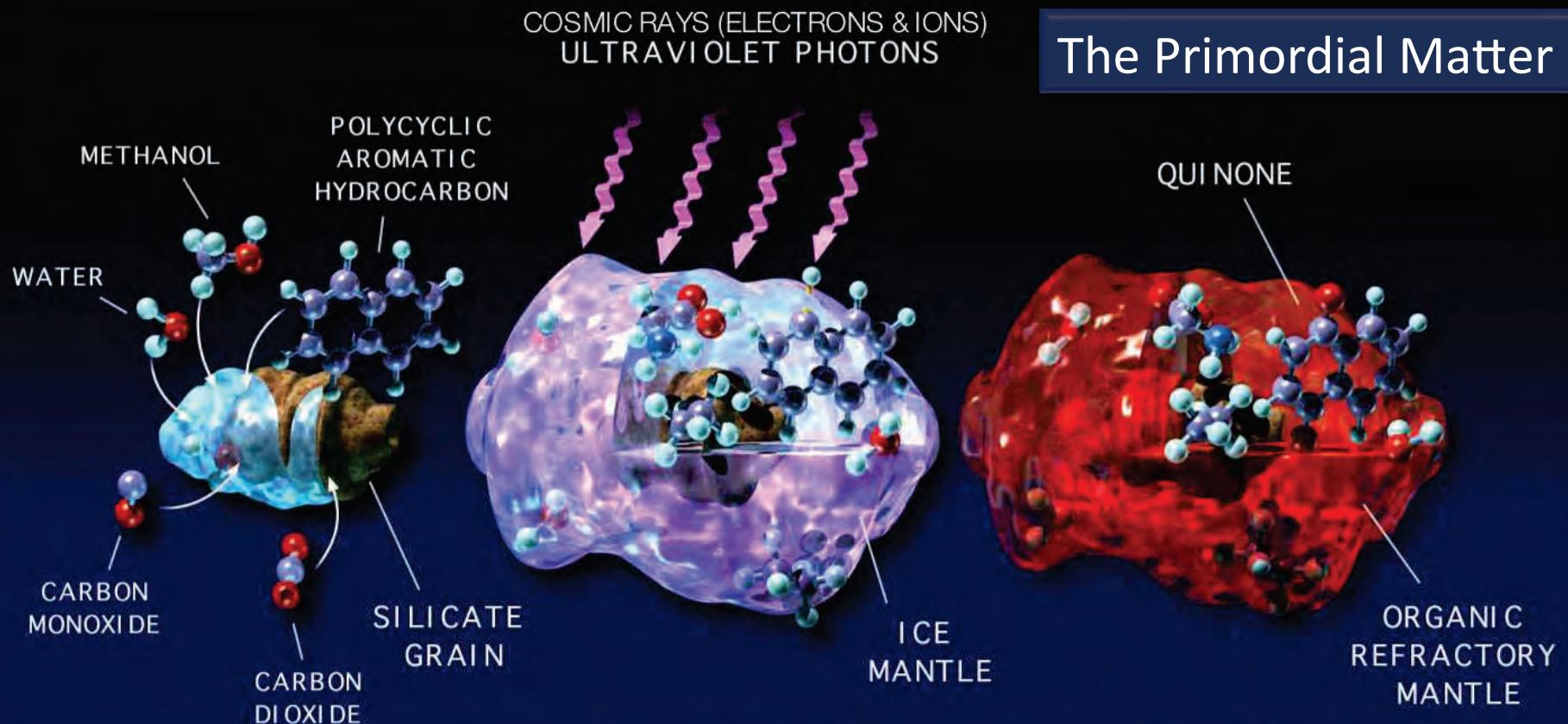
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A better understanding of chemistry and growth of ice grains in cold interstellar medium (JWST...)

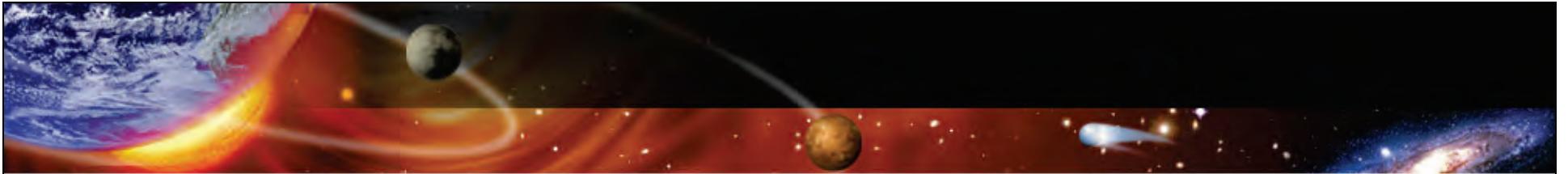
Interstellar Ice Grains: Reservoirs of Building Blocks of Life?

Interstellar ice grains (a few microns size) are made of sand coated with ice containing organic matter. The building blocks of life such as amino acids and quinones are made and stored in these grains that later form comets.

The Primordial Matter



Bernstein, Sandford, Allamandola, Scientific American, July, 1999



Earth's Atmosphere & Surface

Ices and Earth's Environment

Ice strongly reflects Sun's light & heat, while rock and water absorb. Thus, ice helps keep the delicate balance of Earth's surface temperature
(Tom Painter)

Photochemistry of organic pollutants in ices

Atmospheric Ice Aerosols
Cirrus Clouds (~ 8 km, predominantly ice)
Polar Stratospheric Clouds (~20 km)
Polar Mesospheric Clouds (~80 km)



Polar Ice Pollution and Melting



ASTER, HyspIRI (surface ice mass); MLS on Aura (cloud ice), etc.

Retreating Glaciers



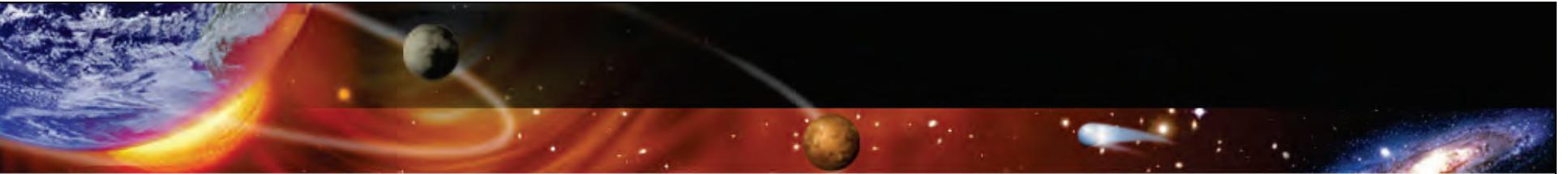
Summary: Why is Ice important to Study?

**Ices are all over in the Universe
and play significant role in:**

- ◆ The origin of life through comet impacts
- ◆ Evolution of solar system bodies
- ◆ Astrobiology – Icy Bodies – Potential Habitable Places
- ◆ Formation stars and solar systems
- ◆ Earth's atmosphere and environment

Understanding Physics and Chemistry of these icy bodies through in-situ & remote sensing missions, along with laboratory studies, is critical to resolve some of the outstanding puzzles in Earth & Space Science Endeavor.

**Indeed majority of NASA's past, present, and future missions
study ices directly or indirectly!**



Let's stay on Earth for a minute before taking off

Ice on Earth – The Real Experience

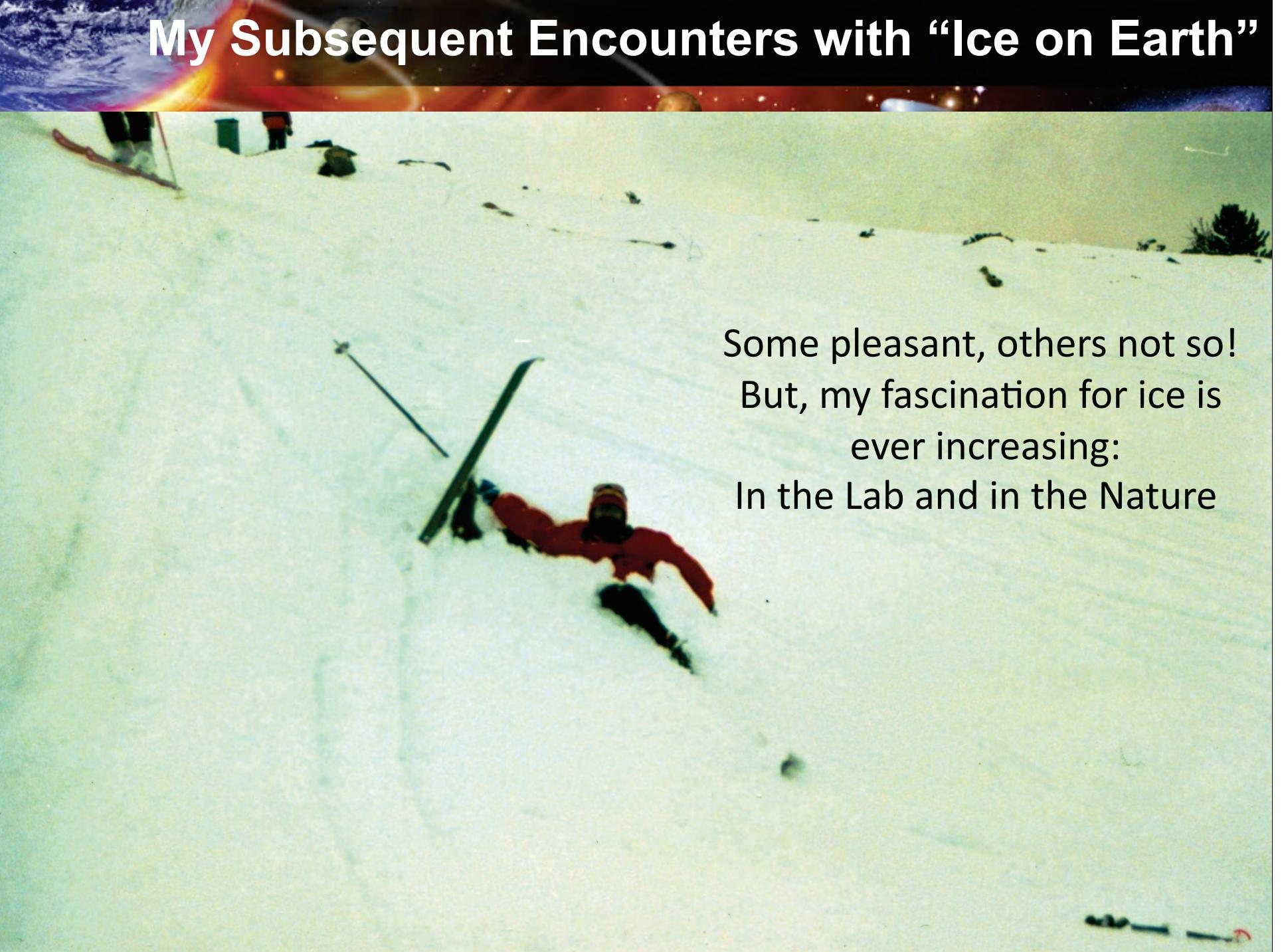


Ice on Earth - My Personal Experience

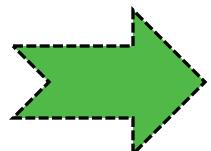
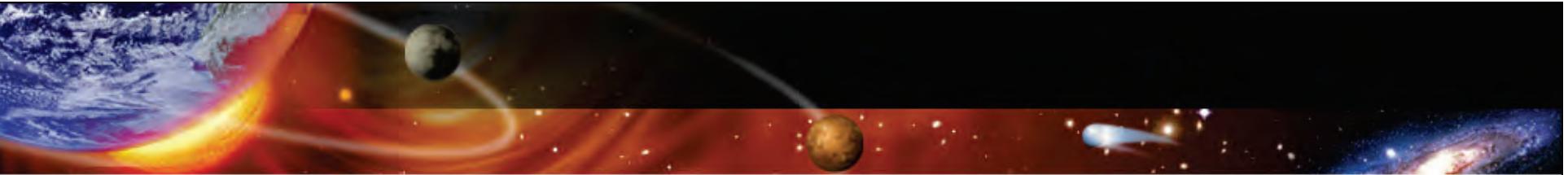


Southern India (Two Seasons: Summer and Monsoon; Hot & Humid)
Typical 120s °F (45 – 50 °C) in Summer, no sign of “Snow or Ice”
Plenty of Water, Fruits, Palms, and Coconuts though!

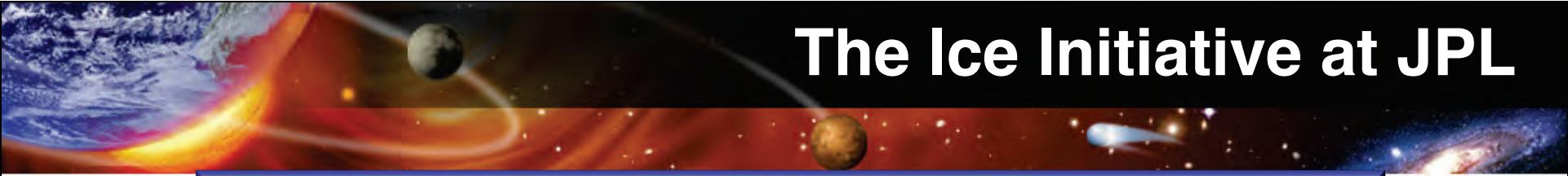
My Subsequent Encounters with “Ice on Earth”



Some pleasant, others not so!
But, my fascination for ice is
ever increasing:
In the Lab and in the Nature



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The Ice Initiative at JPL

The “Strategic Ice Initiative” at JPL includes

Physical Properties of High-Pressure Ices & Clathrates:

Marty Barmatz (Ice Physics)

Julie Castillo (Ice Interiors)

Mathieu Choukroun (Clathrates)

Karl Mitchell (Titan Ice)

Christophe Sotin (Ice Interiors & Clathrates)

Joe Young (Ice Physics)

Fang Zhong (Ice Physics)

Spectroscopy & Radiation Chemistry of Ices

Brad Dalton (NIR Spectroscopy; Ices, Sulphates & Europa)

Murthy Gudipati (VUV-FIR Spectroscopy; Ices, Radiation, Chemistry, and Organics; Titan)

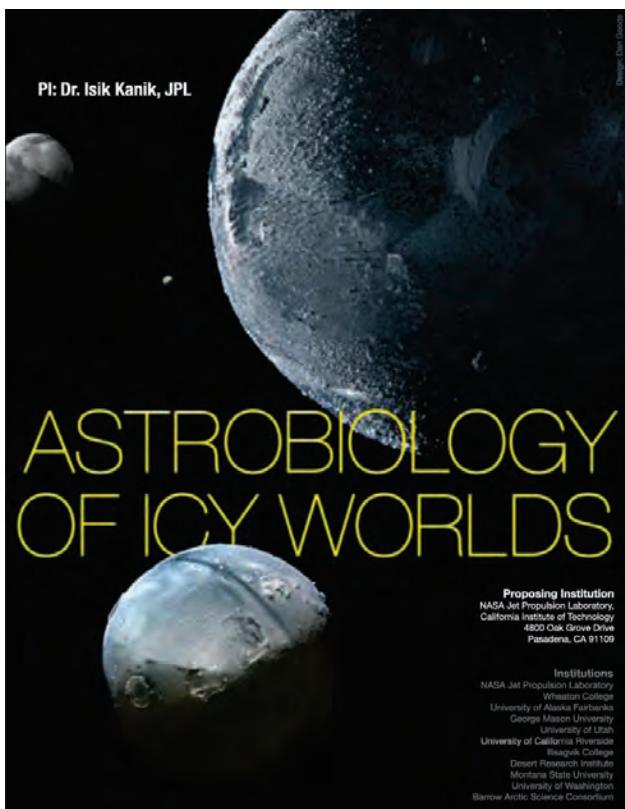
Kevin Hand & Bob Carlson (Ice, Radiation, Life, and Europa)

Paul Johnson & Robert Hodyss (Ice, Radiation, & Chemistry; Titan)

NASA Astrobiology Institutes (NAI) at JPL

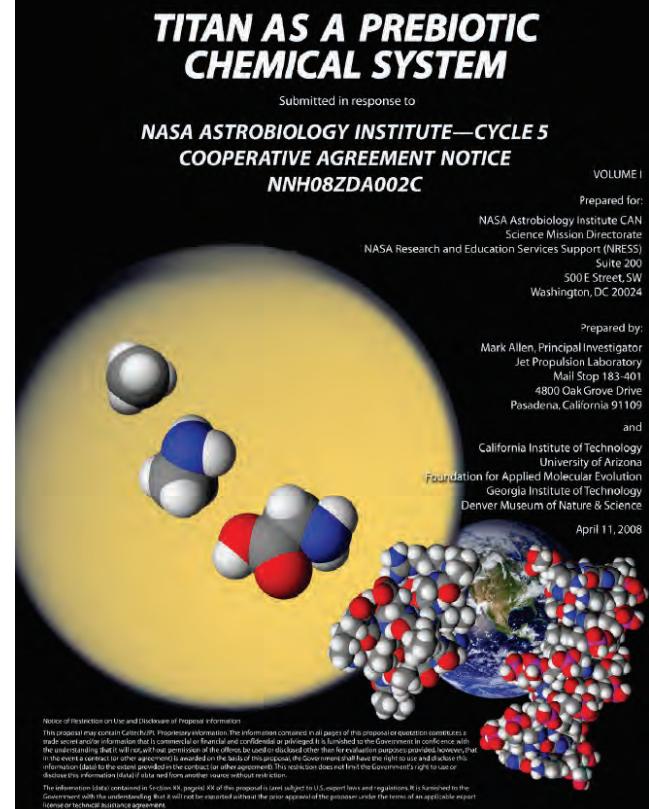
“Strategic Ice Initiative” enabled JPL to win TWO NAI Grants;
Gearing up JPL towards future
Flagship Missions to Jupiter/Saturn Systems, Mars In-Situ Missions, etc.

Icy Worlds (Isik Kanik, PI)

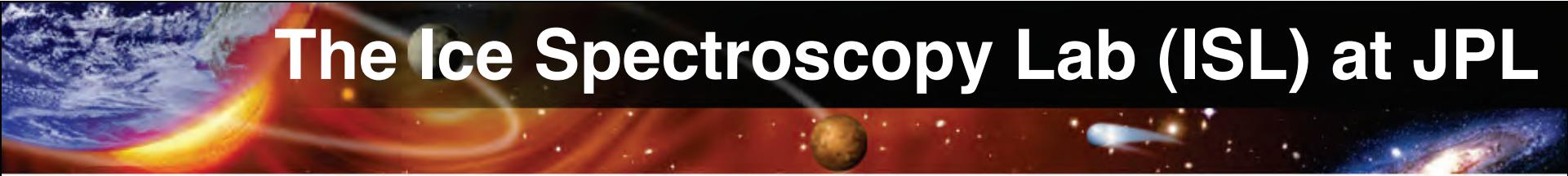


To Understand
Habitability,
Survivability,
and
Detectability
of Life in/on
Icy Bodies
&
Evolution of
Prebiotic
Molecules on
Titan (similar
to Earth)

Titan Chemistry (Mark Allen, PI)



The Ice Spectroscopy Lab (ISL) at JPL



At ISL, our Research is focused towards understanding the
“Evolution of Earth’s, Planetary, Cometary, and Interstellar
Ices”

Including the Possible Origins of Life

AND

Support present and future JPL/NASA Missions
through providing

Science Insight
Lab Data to interpret the Mission Data
Next Generation Instrumentation.

The Ice Spectroscopy Lab (ISL)

Murthy Gudipati
(PI)

Rui Yang

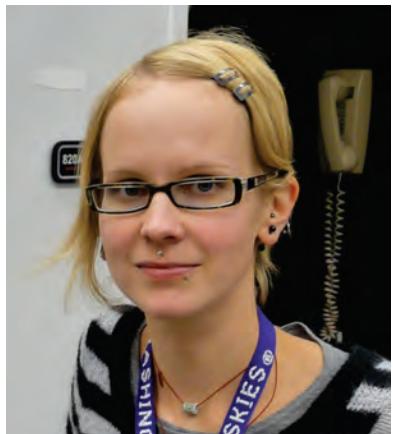
Irene Li-Barnett (UMD)

Antti Lignell

Ronen Jacovi

Graduate Students

Visiting Scientists



Hanna Lignell
(UC Irvine &
University Helsinki)

Uniqueness of ISL
(in JPL's Spirit)
Bring Suite of Analytical
Instruments to the Ice
Sample - Simultaneous
Multiwavelength
Spectroscopy!

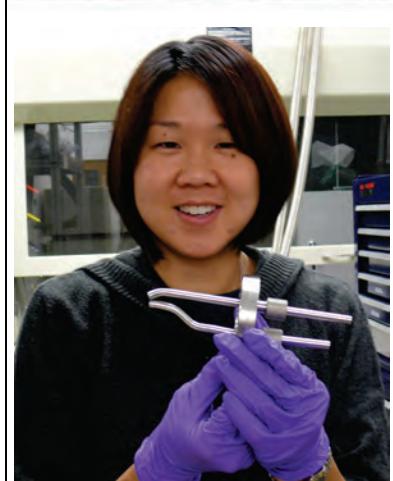


Eleonora Ammannito
INAF, Rome, Italy



Isabelle Couturier
CNRS & U. Marseille,
France

ISL Instrumentation Fleet: P-Irene



Irene Li-Barnett

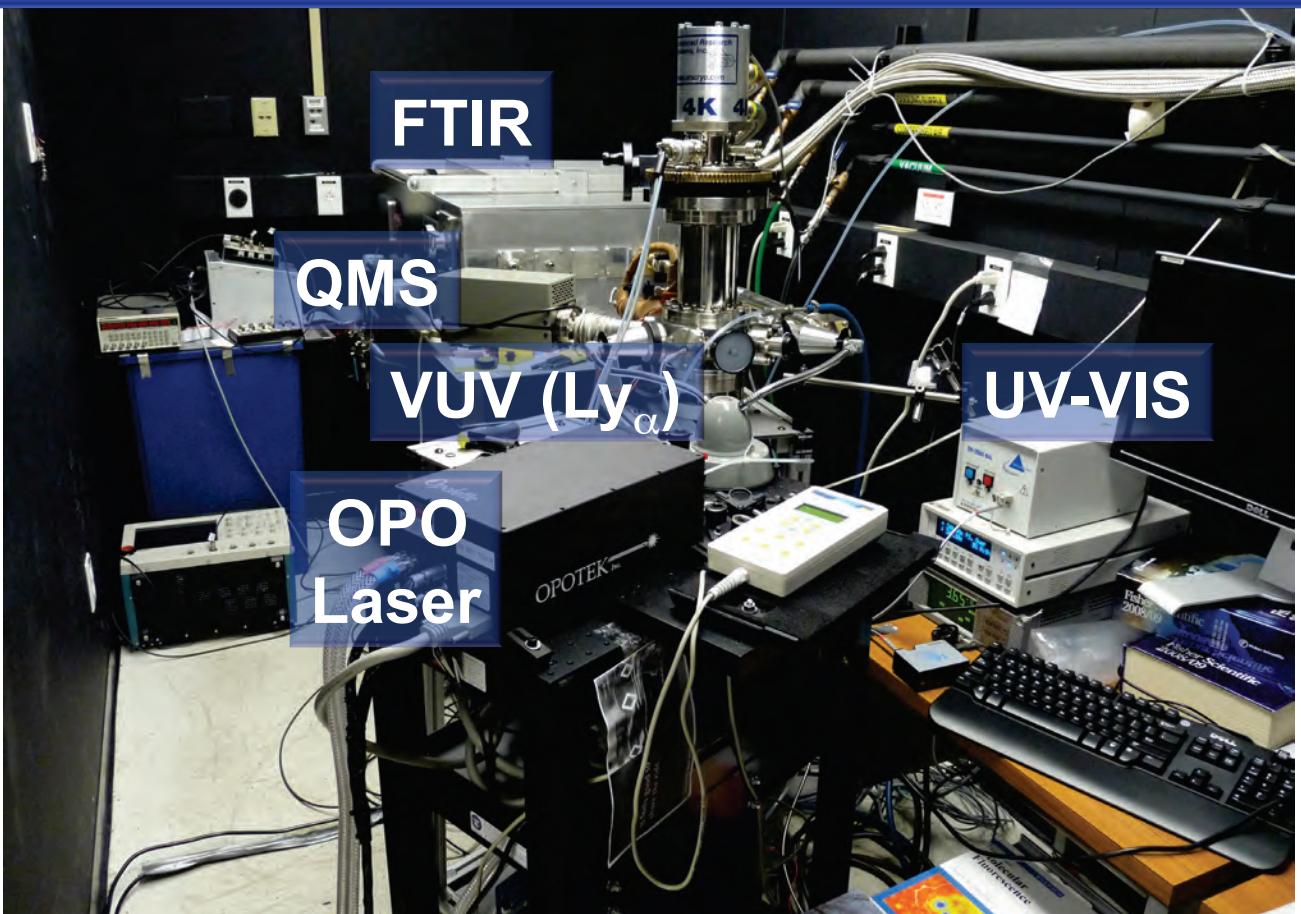


Antti Lignell

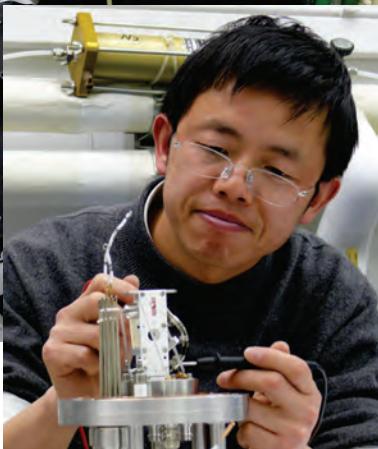
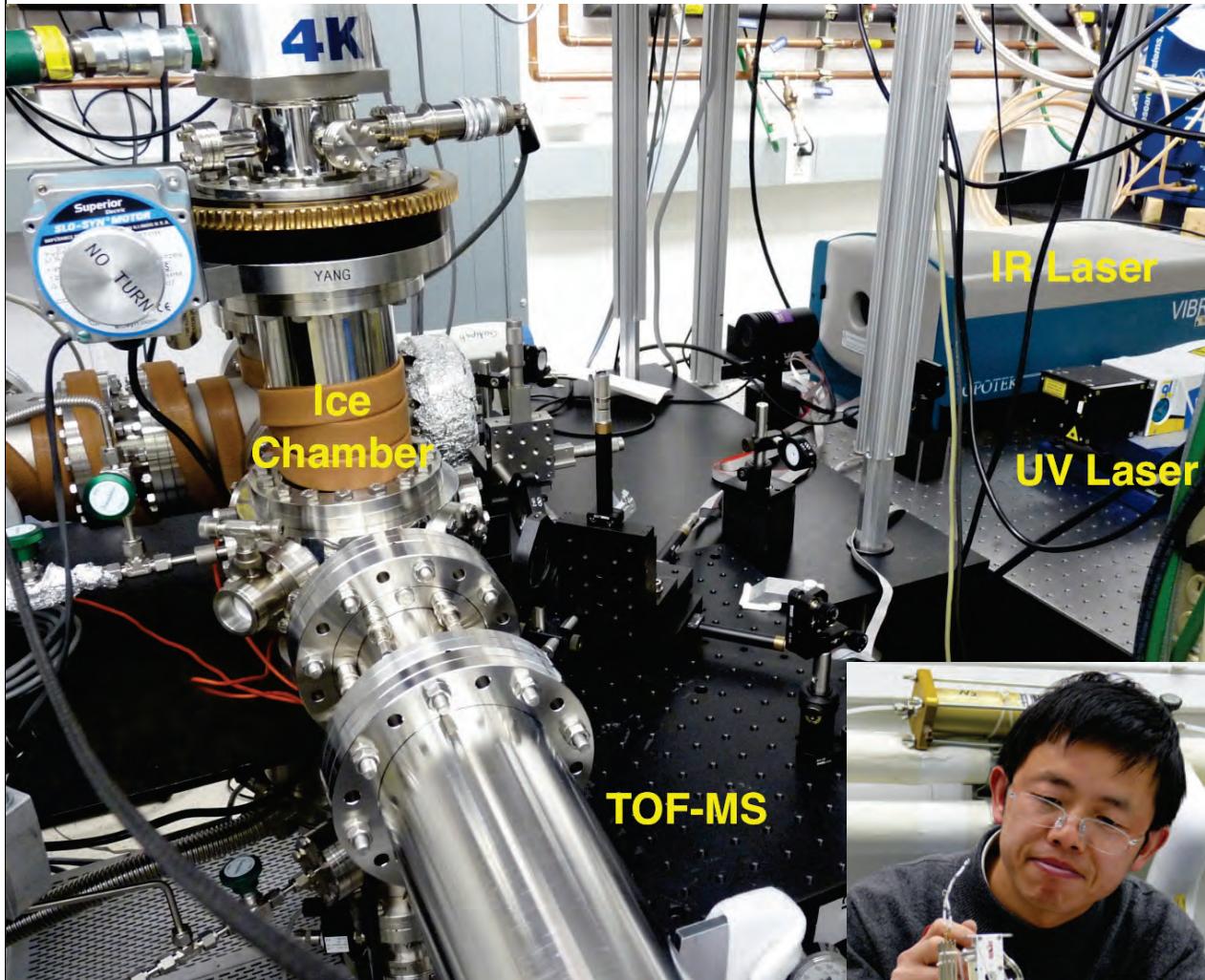
P-Irene (named after Irene)

Studies: Radiation chemistry and spectroscopy of PYRENE (and other polycyclic aromatic hydrocarbons, PAHs) in ice.

Chemistry of Ice & Organics on Earth, Europa, Enceladus, etc.,



ISL Instrumentation Fleet: Yang



Two weeks ago Rui & Wu became proud parents of their son “Jet”

Yang (named after Rui Yang)

This is our flagship experimental station with state-of-the-art instrumentation.

Studies: Understanding intricate details of how biomolecules could have evolved or degraded in **Interstellar Ices (Origin of Life)**, Comets and on **Europa’s Surface** (NASA Icy Worlds NAI).

Future Instrumentation

Rui Yang

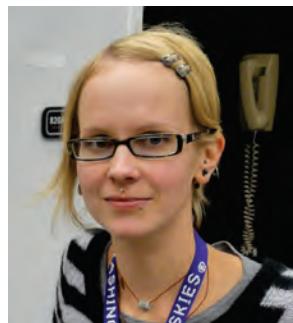
ISL Instrumentation Fleet: Acquabella

Acquabella (“Water the beautiful” in Italian)

Assembled by Eleonora and Antti; Studies: Spectroscopy of cometary ices (Rosetta), PAHs in ices (Spitzer/Rosetta), and Titan’s molecules (NASA Titan NAI).



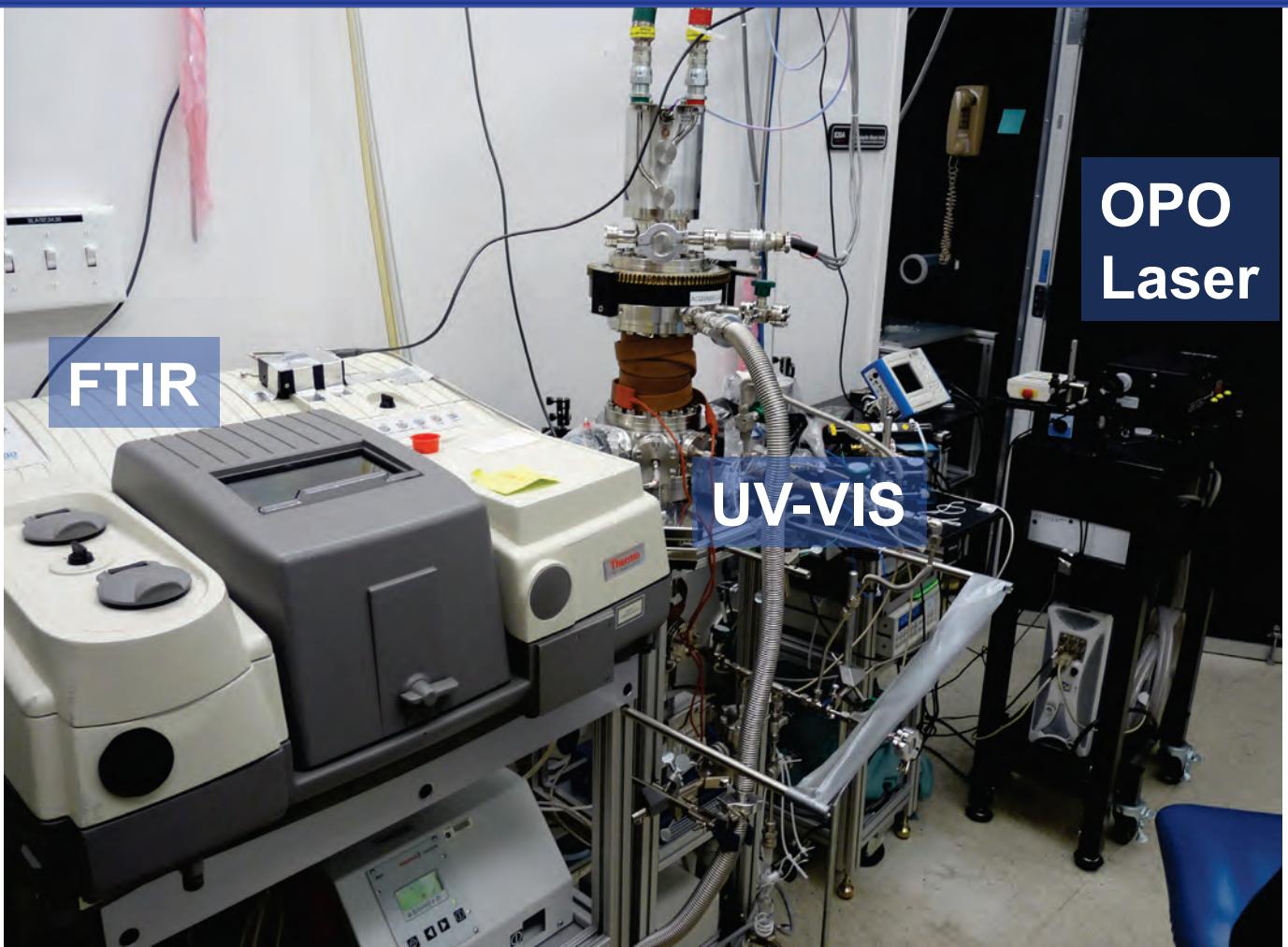
Eleonora Ammannito



Hanna Lignell



Ronen Jacovi





ISL Instrumentation Fleet: Himalaya

Himalaya (“Dwelling of Snow” in Sanskrit)

Named after highest snow ranges on Earth.

Studies: This powerful cryogenic system is under construction. Large scale amorphous ices will be grown to study their physical and chemical properties.

Star formation; Comets; Origins of Life



Antti Lignell



Murthy Gudipati



ISL Instrumentation Fleet: TOAST Lab

Titan Organic Aerosol and Surface ChemisTry (TOAST) Lab

Also known as Jacovi's Titan Kitchen - a fully equipped synthetic organic chemistry lab.

Studies: To understand photochemistry in **Titan's lower atmosphere** and cosmic ray chemistry of **Titan's surface** (Titan NAI).

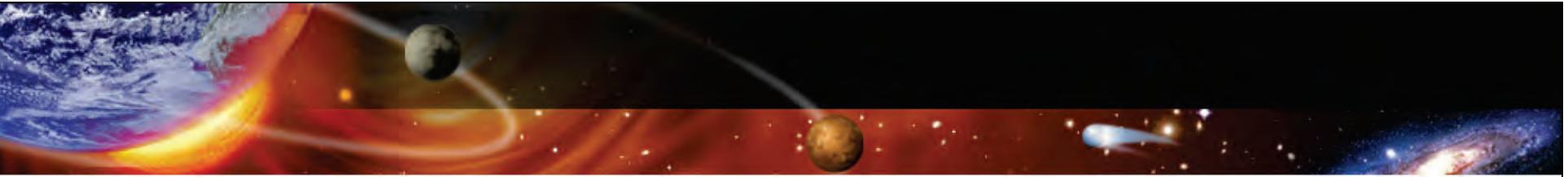


Ronen Jacovi



Isabelle Couturier





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- **New Science Results from ISL**
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- **Some outstanding issues**
- **Summary & Future**

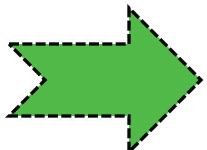
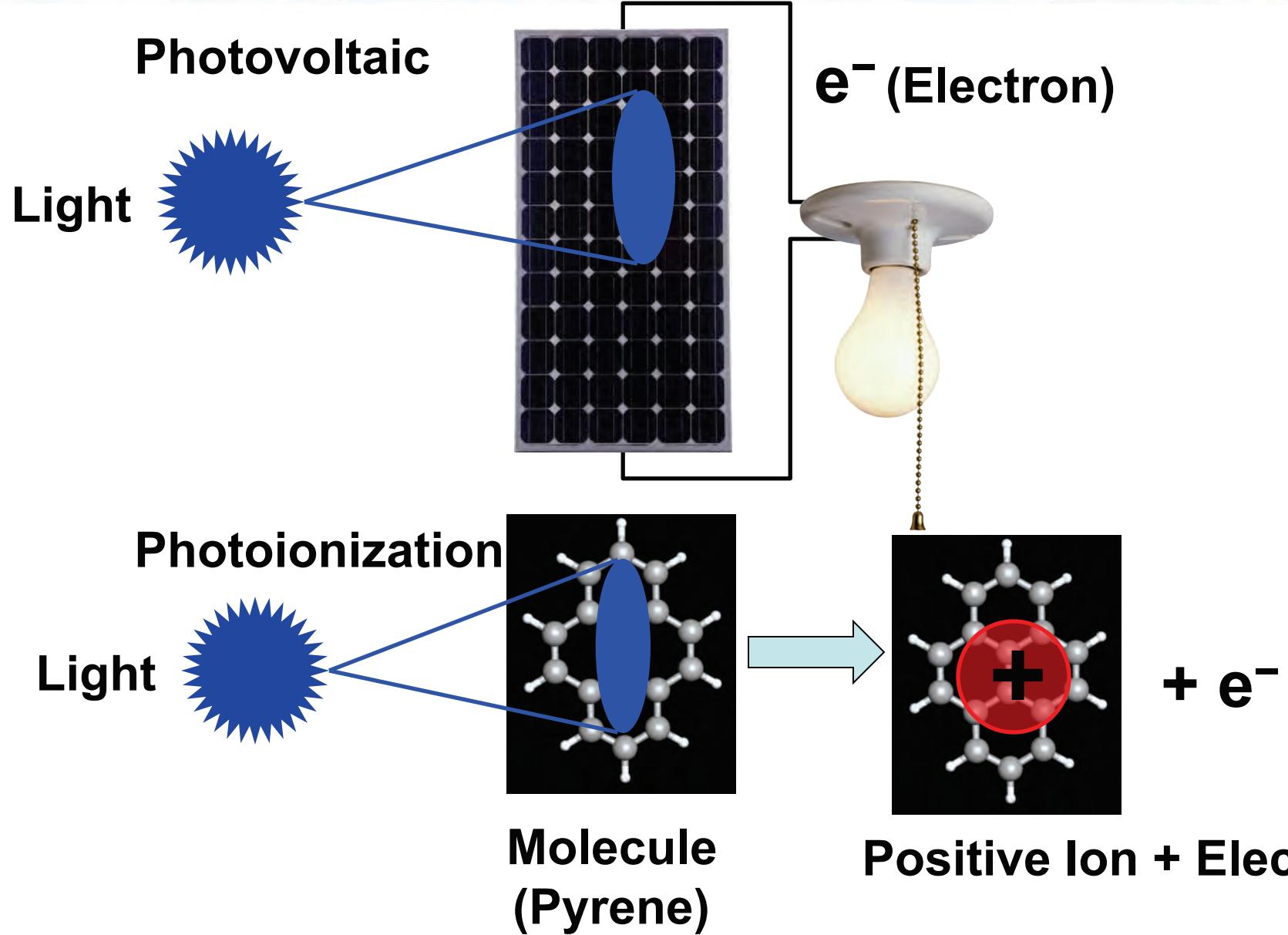
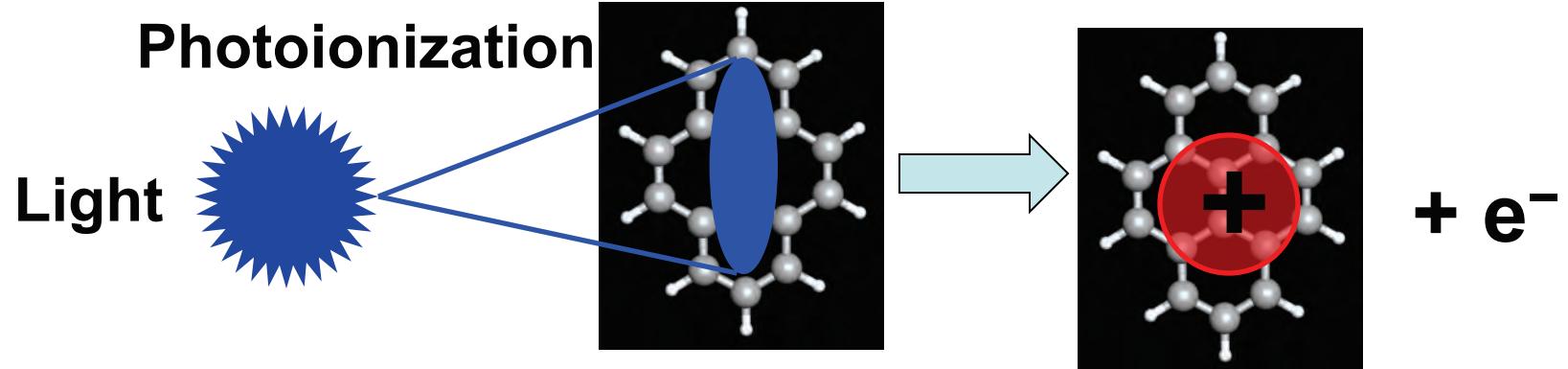


Photo-Ionization



New Finding: Ionization of Organics in Ices needs less Energy

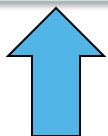


**Molecule
(Pyrene)**

Positive Ion + Electron
Charged & Very Reactive

Light

Rainbow Colors



**Normal
(Ultraviolet)** **In Ice
(Visible)**

Organic
Photoionization in
Cloud & Surface Ice

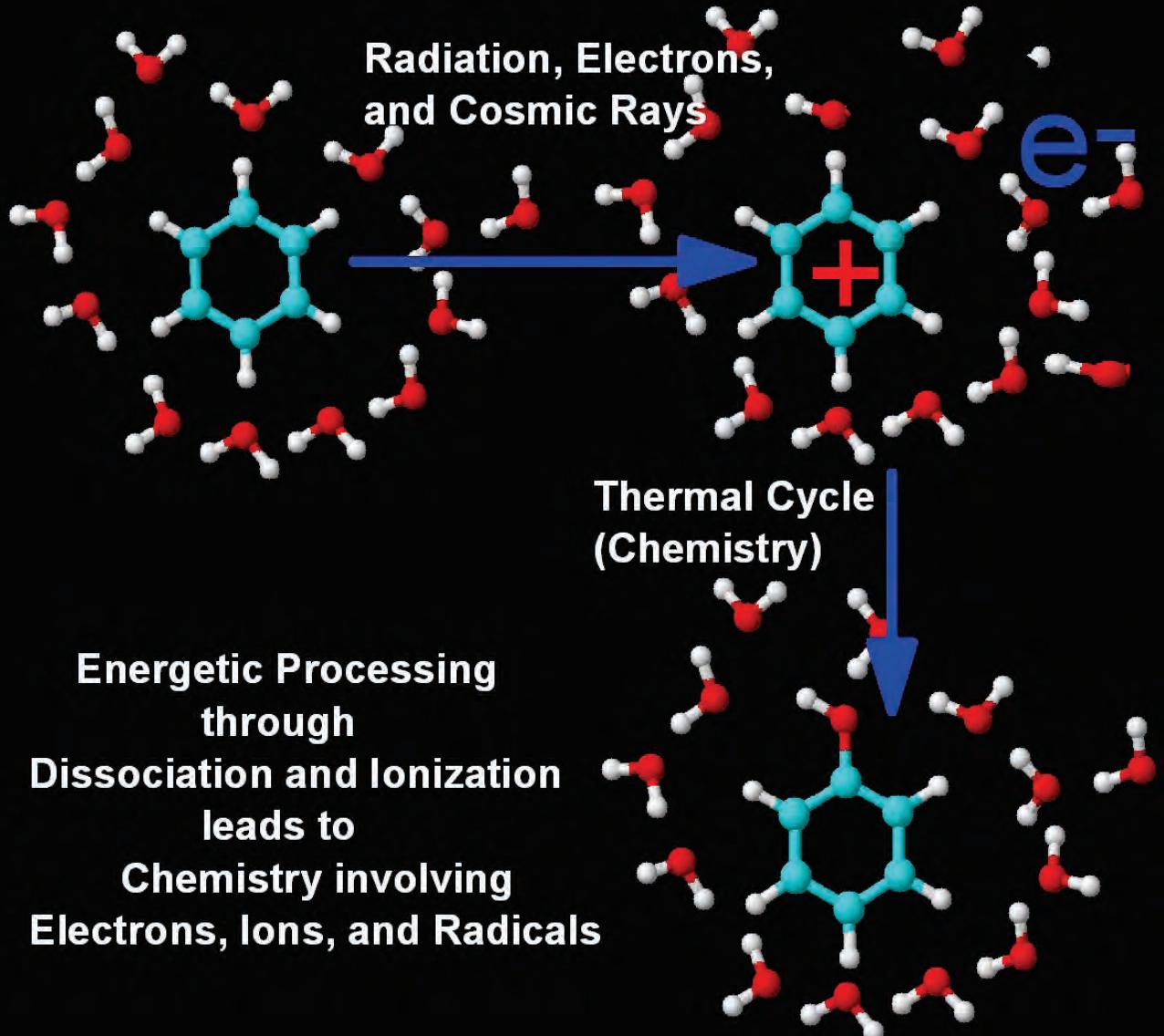
Less Energy Photons

Gudipati JPhysChem 2004; Gudipati & Allamandola ApJ 2006;
Antti Lignell & Murthy Gudipati (2010; to be published)

New Chemical Pathways (Brewing) in Ice

Solar Radiation (Light, electrons, and ions) and Galactic Cosmic Rays (electrons and ions) carry sufficient energy to cause physical and chemical changes in ices.

Individual particle (photon) energy and the flux determine the equilibrium state of these ices.

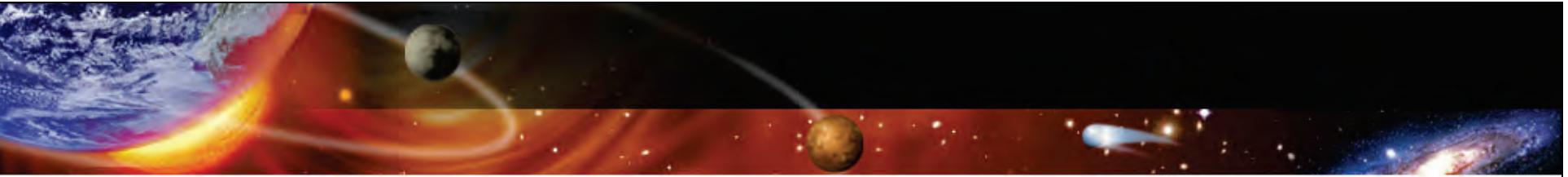




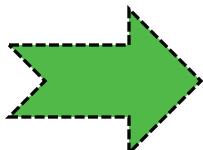
Quick Summary of Some of the New Results from ISL

Laboratory Research brings new Insight into Physics and Chemistry of Icy Bodies in the Universe, including on Earth

- ◆ Ice is no “passive and inert” solid – but as active as a volcano!
- ◆ Ice facilitates chemistry of organics under radiation.
- ◆ Ices containing organic pollutants can easily be charged by Sun’s ultraviolet and visible light.
- ◆ Organic molecules in ice are easily oxidized (alcohol, ketone, acid) even at 5 K (-268 °C; -450 °F) under radiation.
- ◆ Oxidized organics are strongly bound to ice.
- ◆ Low-energy electrons damage organics in ice far deeper than present models predict.
- ◆ Titan’s atmospheric photochemistry continues to occur at much lower altitudes (< 100 – 200 km) and on surface.



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Photochemistry in places not thought before?

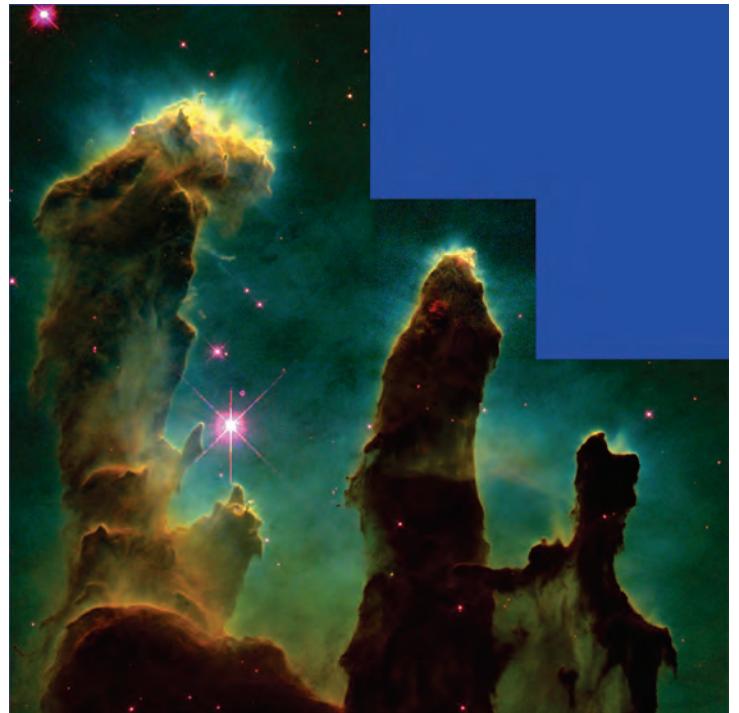
- ◆ Ice facilitates photochemistry of organics (low-energy)
- ◆ Ices are easily charged under Sun's ultraviolet and visible light, when containing organic pollutants.

1. Charge mediated photochemistry in lower atmosphere (cirrus clouds) and in glaciers/ polar ices containing organic pollutants?
2. Charge mediated cloud dynamics?



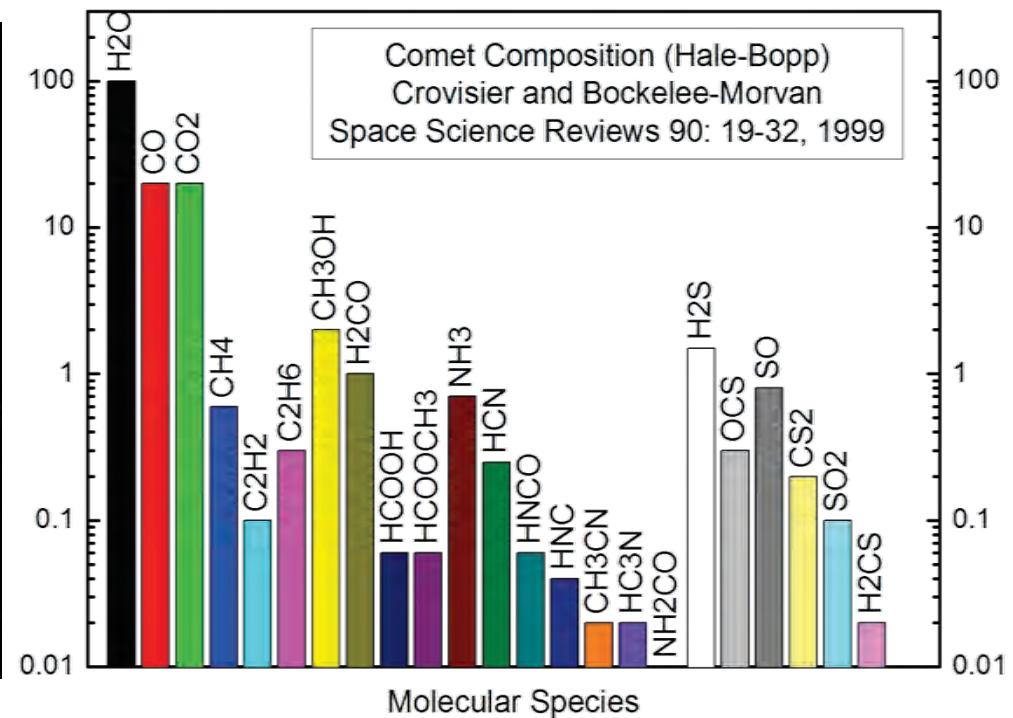
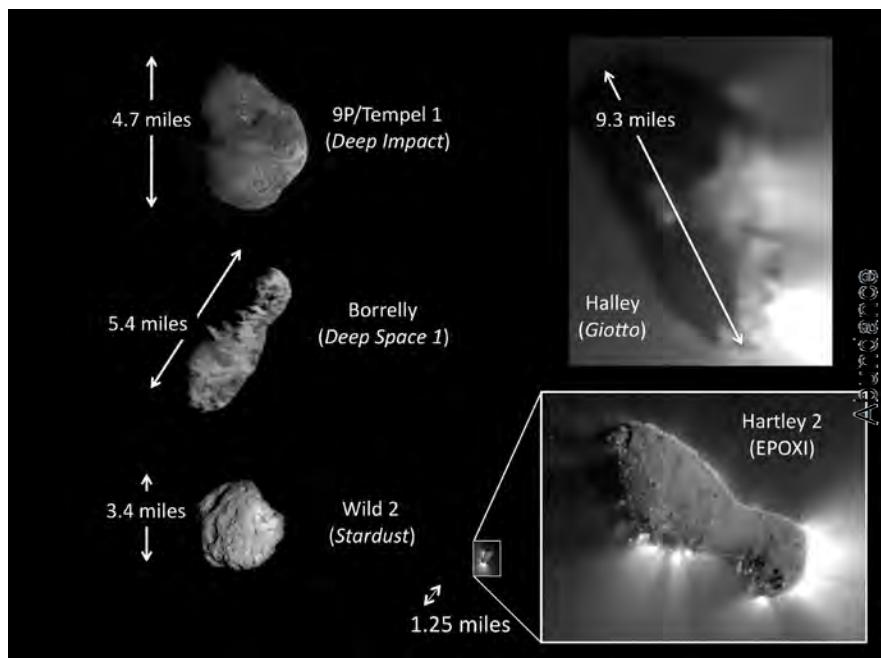
Positive and negative charges facilitates stronger binding of ice particles together through Coulomb Forces

1. Photochemistry deeper into dense molecular clouds?
2. Nucleation of molecular clouds through charged ice grains?



Composition of Comets Explained?

- ◆ Organic molecules in ice are easily oxidized (addition of oxygen) even at 5 K under radiation.
- ◆ Oxidized organics are strongly bound to ice

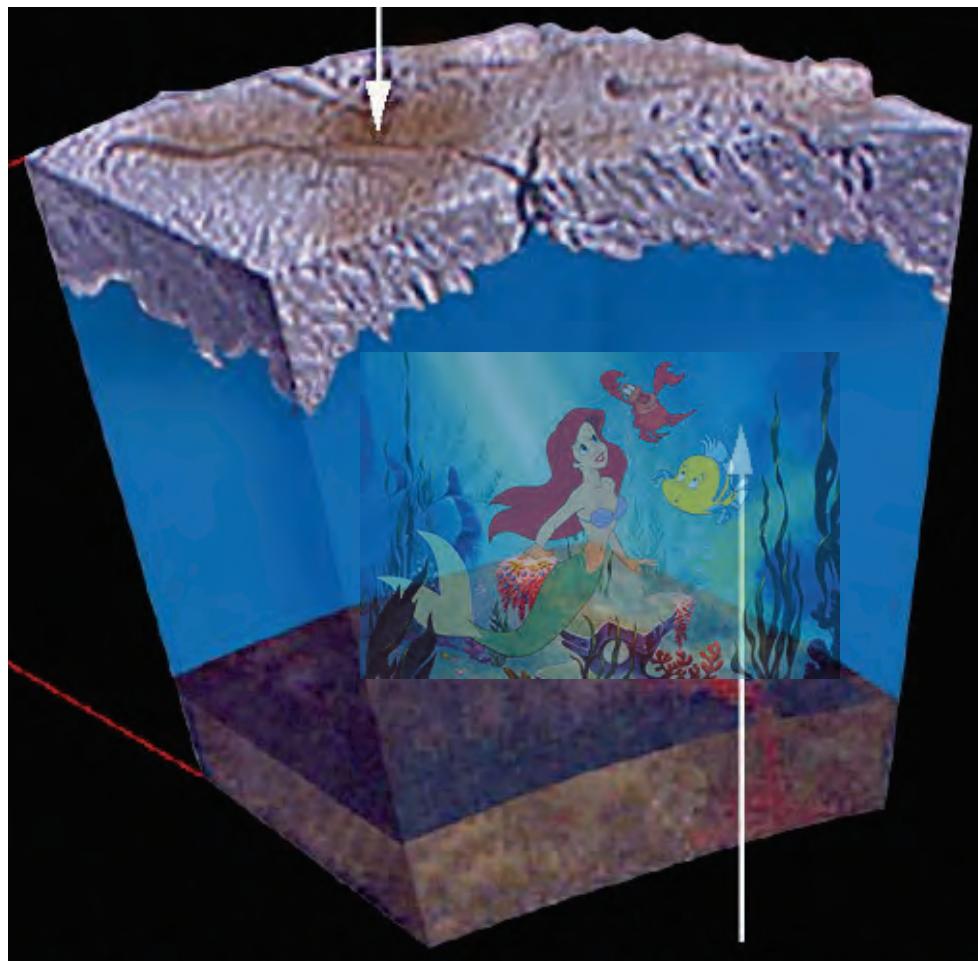


Gudipati & Yang (2010, to be published)

High abundance of oxidized organics: Methanol & Formaldehyde

How deep do we need to dig in ice to find life?

- ◆ Low-energy electrons damage organics in ice far deeper than present models predict



If there are oceans and life on Europa, can signatures of life be seen on Europa's surface? Or are they destroyed by the harsh radiation from Jupiter?

How deep do we need to dig through Europa's surface, where potential life could be protected?

Deeper than present models predict at (~1m)?

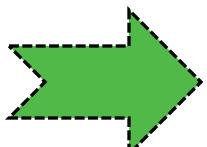
How does material and energy transport occur through ice mantle on Europa?

Quantitative answers are critical for the in-situ payload of future flagship missions to Europa (such as EJSM).

Gudipati, Li-Barnett, Lignell, Jacovi (2010, to be published)



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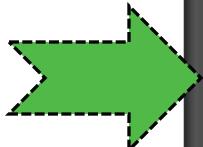




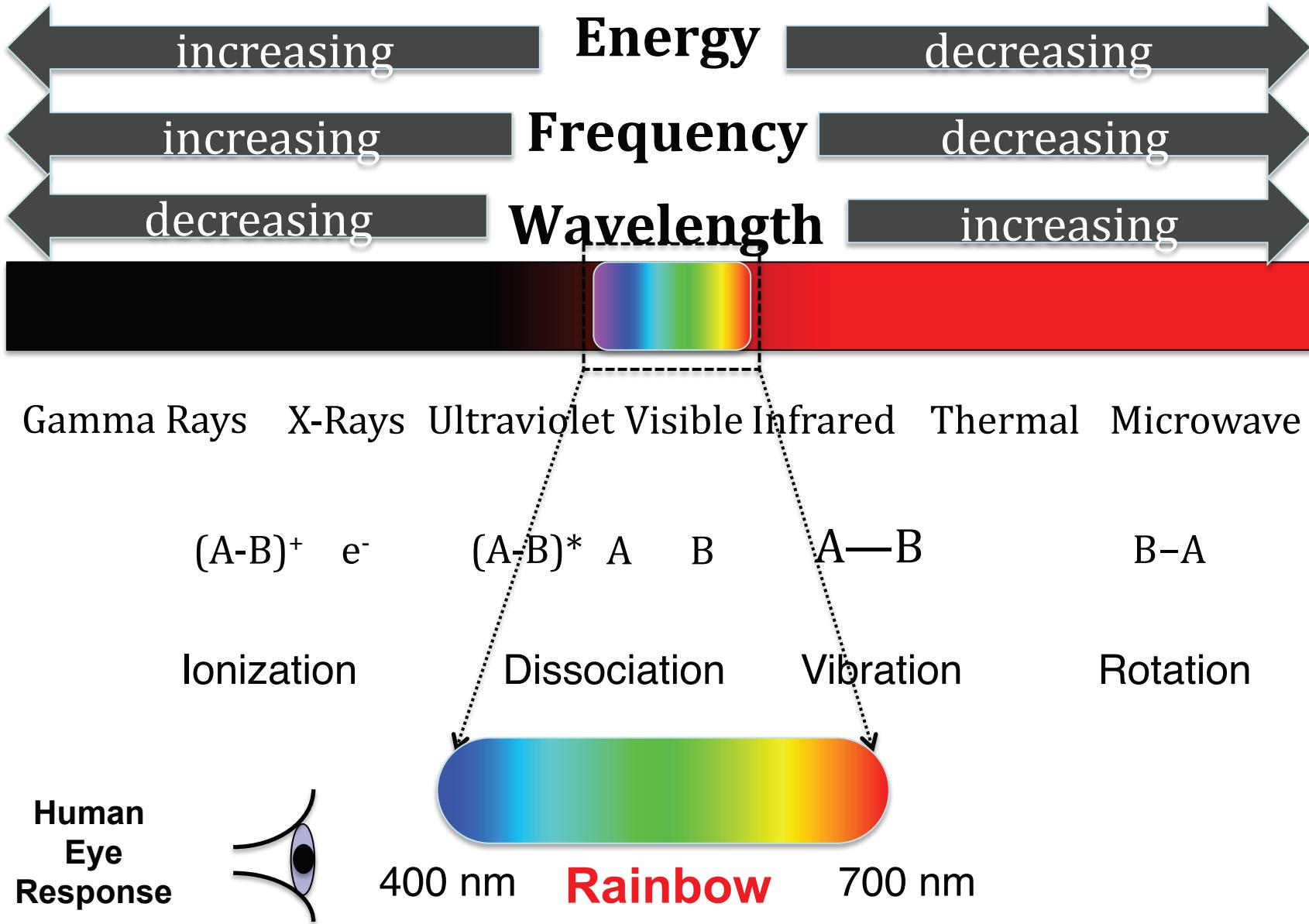
Outstanding Questions

There are many outstanding questions, including:

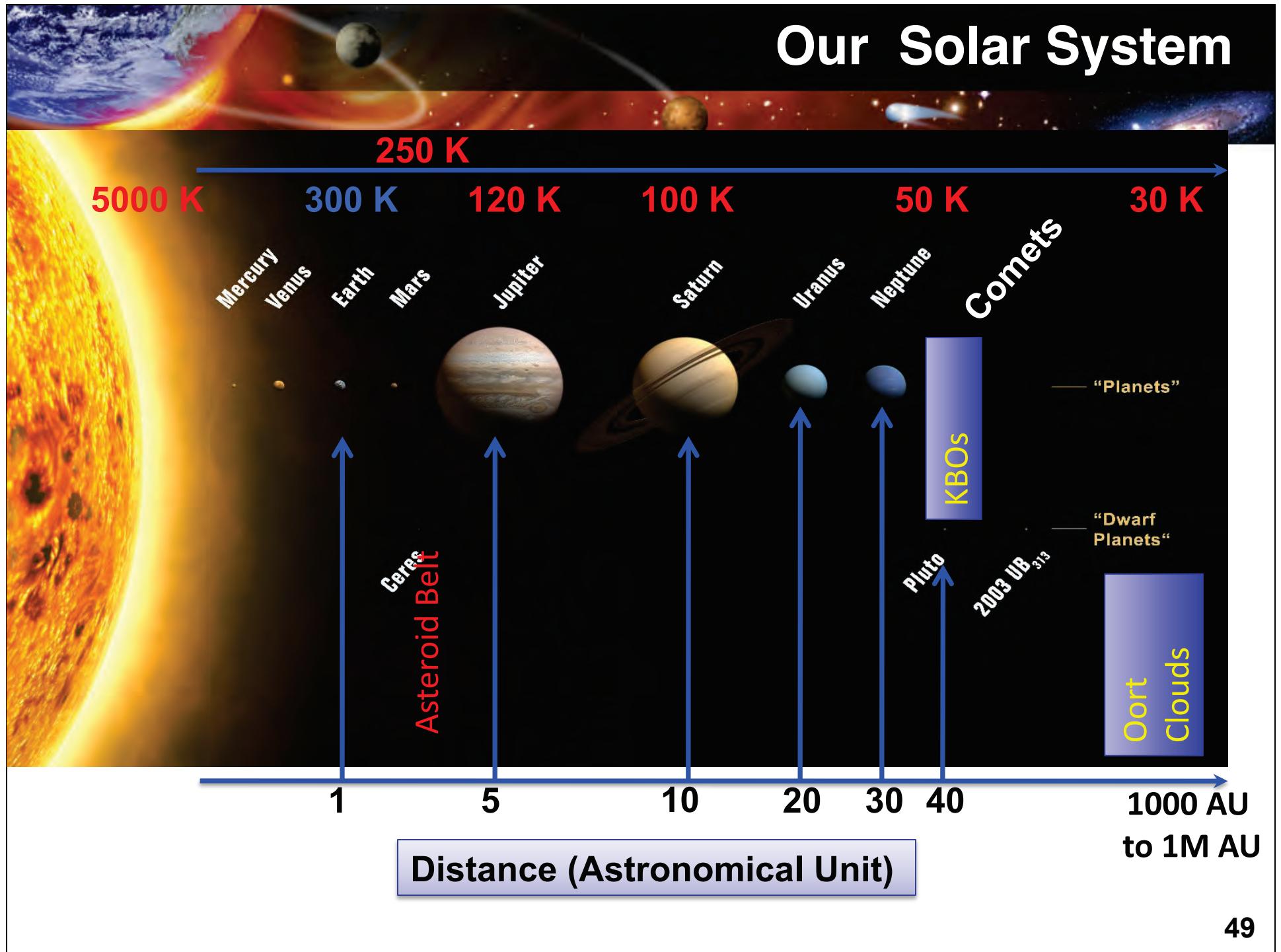
- Influence of pollutants on ice chemistry and physics in Earth's atmosphere and on the surface.
- Ice on the Moon – how is it formed?
- Are there organics in subsurface ices of Mars?
- Constraints on habitability of icy bodies (e.g. Europa)?
- Plumes of Enceladus how are they formed?
- Saturn's icy Rings – what is their bulk composition?
- Comets – do they preserve primordial interstellar material?
- How reactive are interstellar ice grains?
- What is the role of amorphous ices in the Universe?



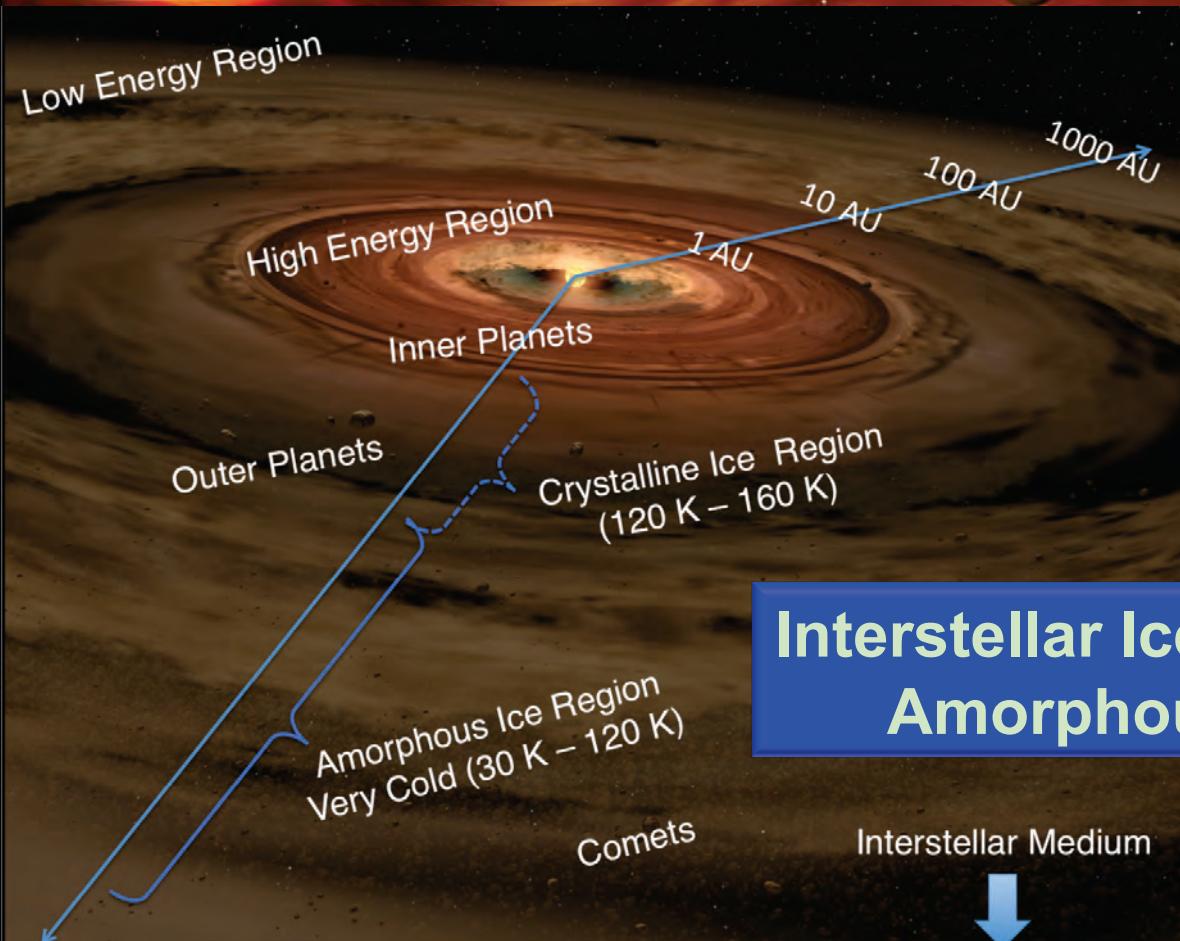
Electromagnetic Spectrum (Light)



Our Solar System

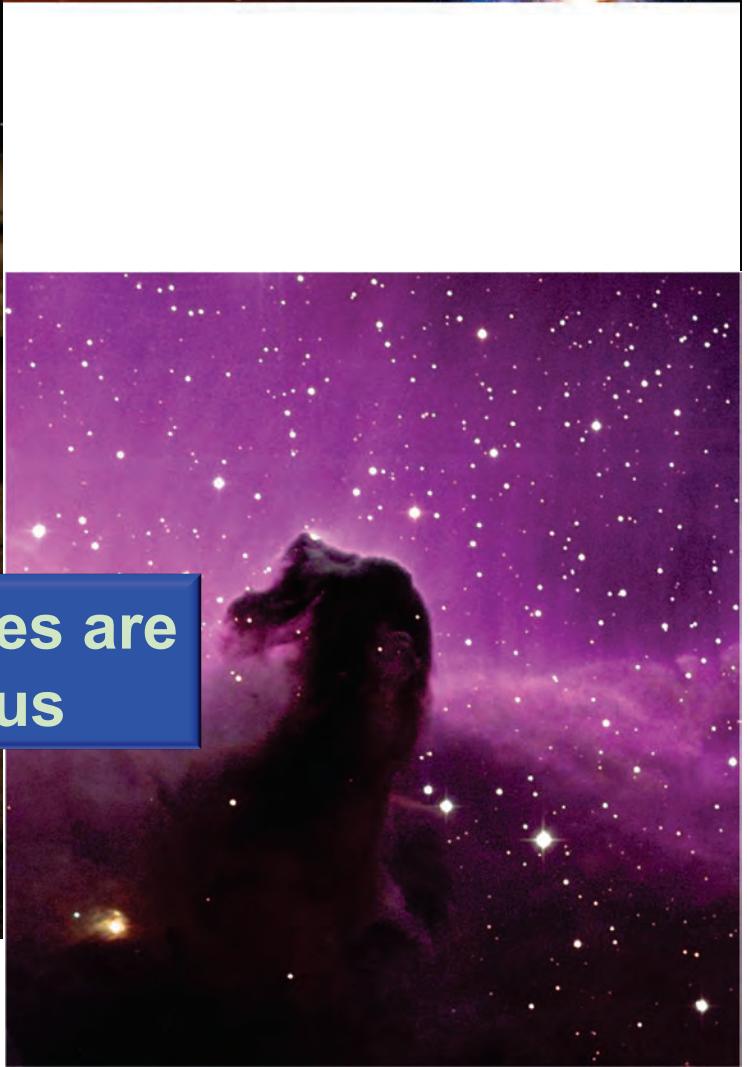


Comets – Connecting Stars and Interstellar Matter

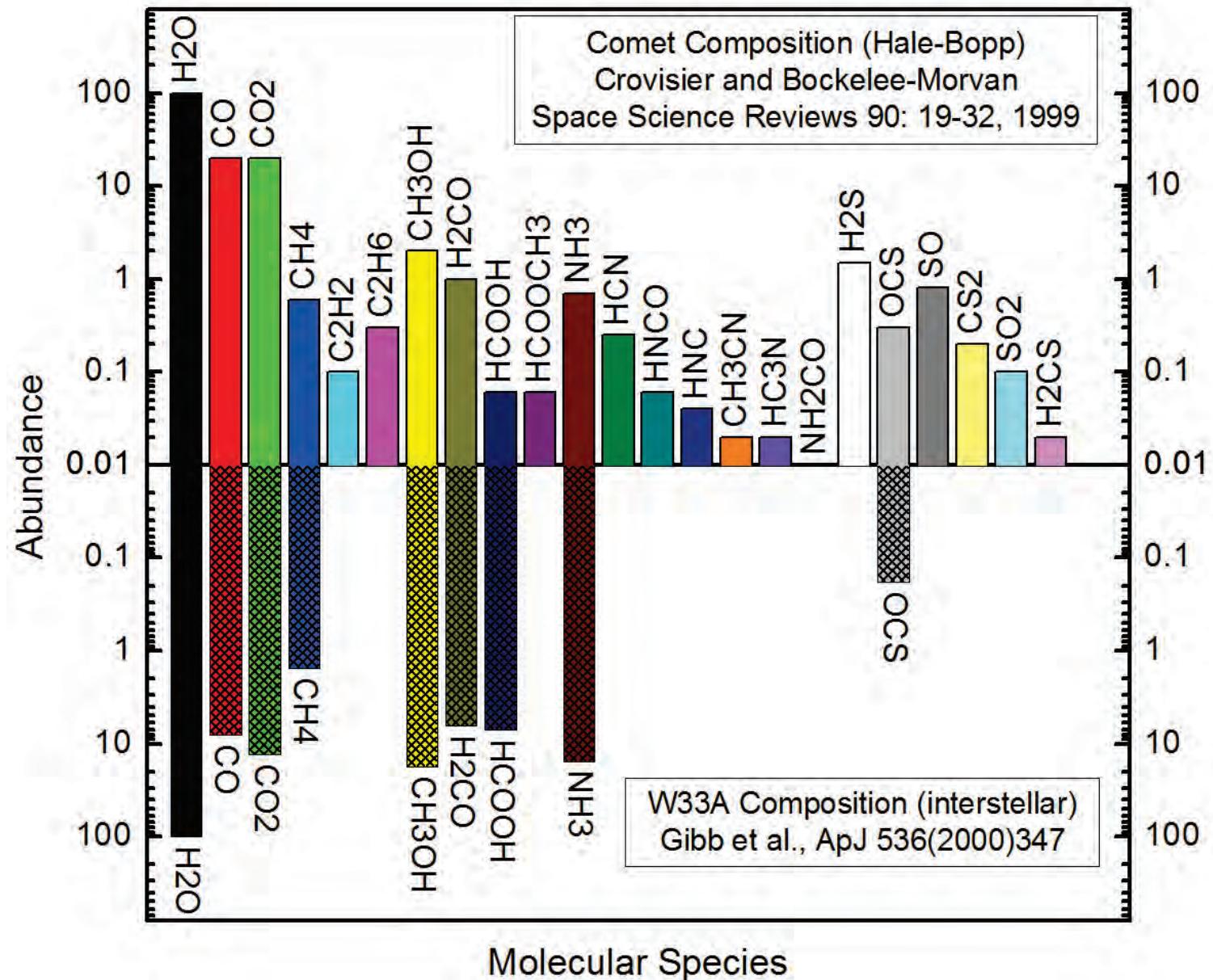


Interstellar Ices are
Amorphous

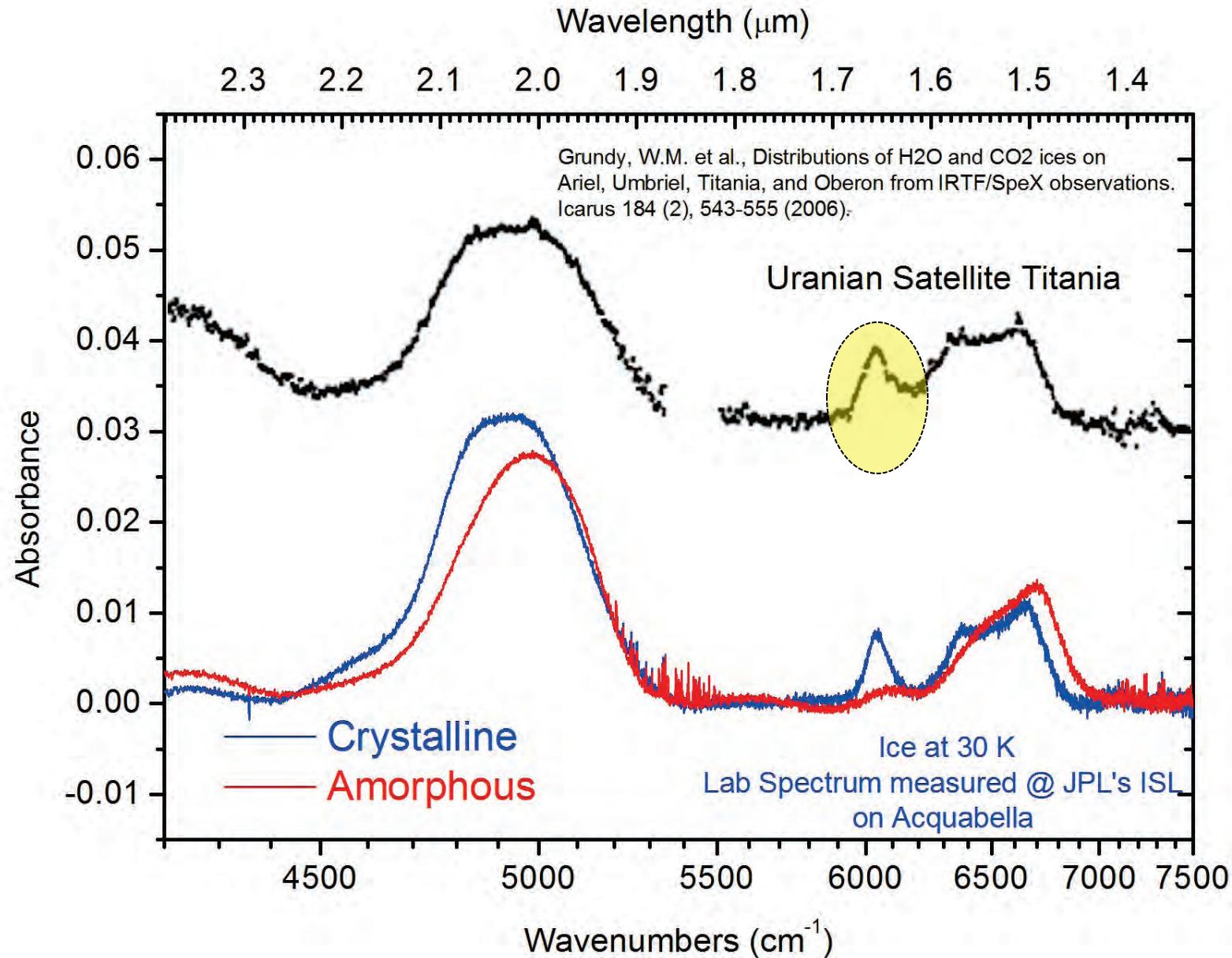
Interstellar Medium



Similar Composition: Comets and Interstellar Ice Grains

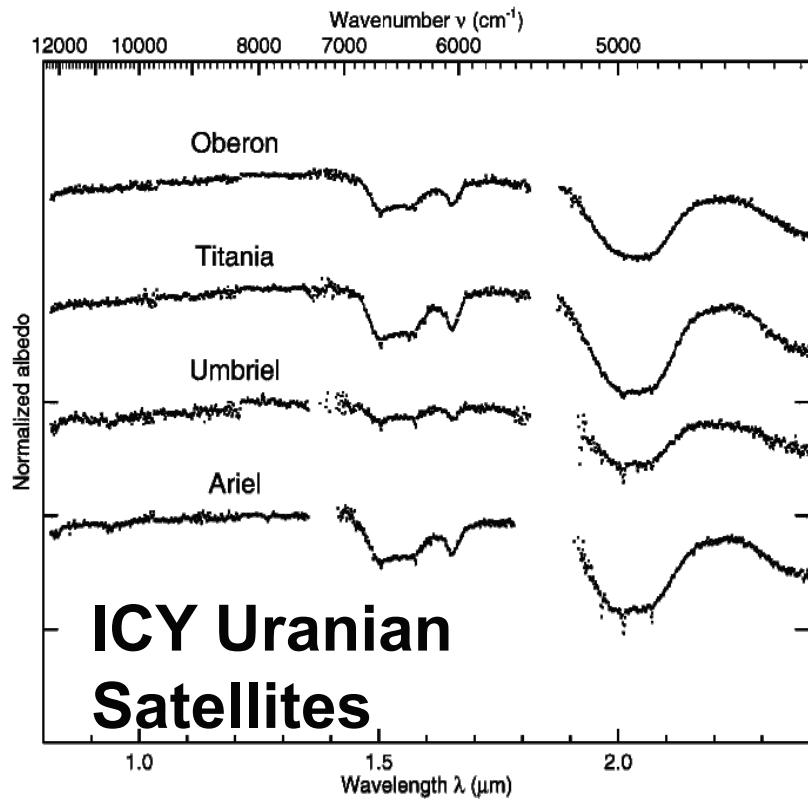


Fingerprints of Amorphous and Crystalline Ices

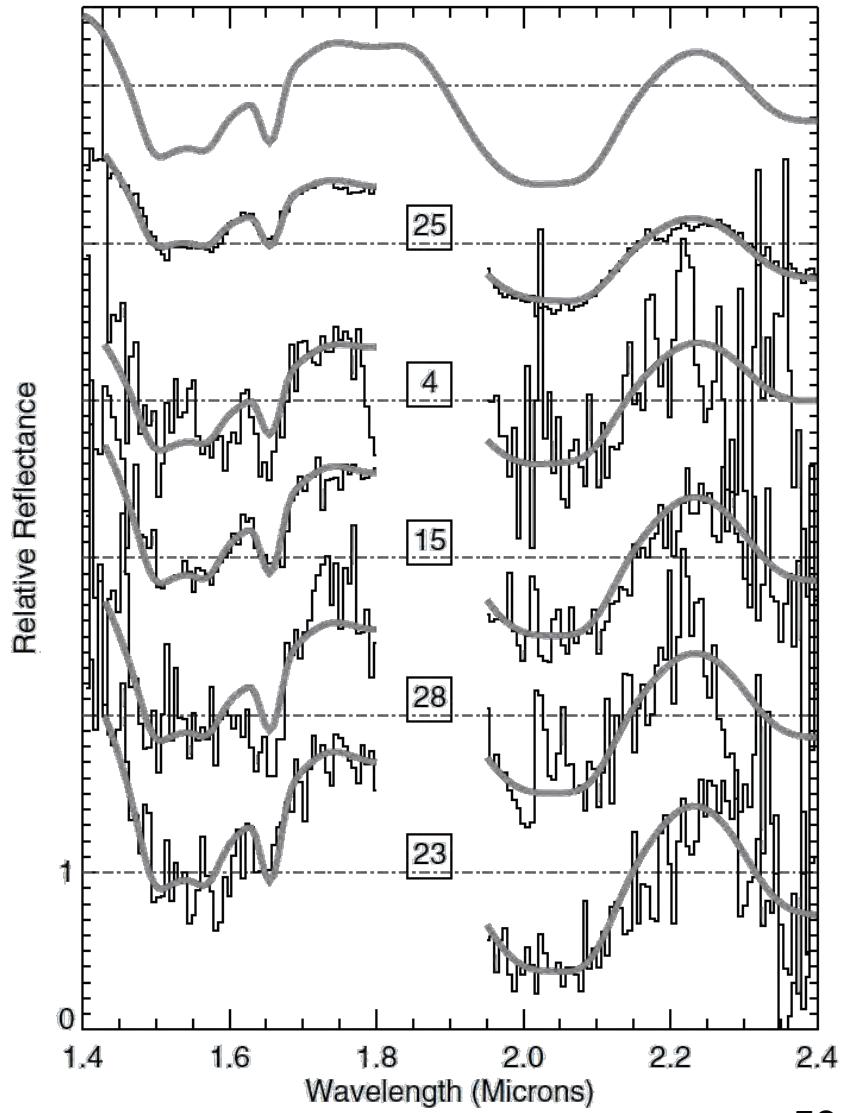


Crystalline Ice on Uranian Moons & KBOs

Grundy et al. / Icarus 184 (2006) 543–555



Barkume, Brown, Shaller;
Astronomical Journal 135:55–67, 2008



Observations:

Even very cold objects (<50K) show some crystalline spectral properties in the solar system. ONLY interstellar ices show amorphous signatures – WHY?

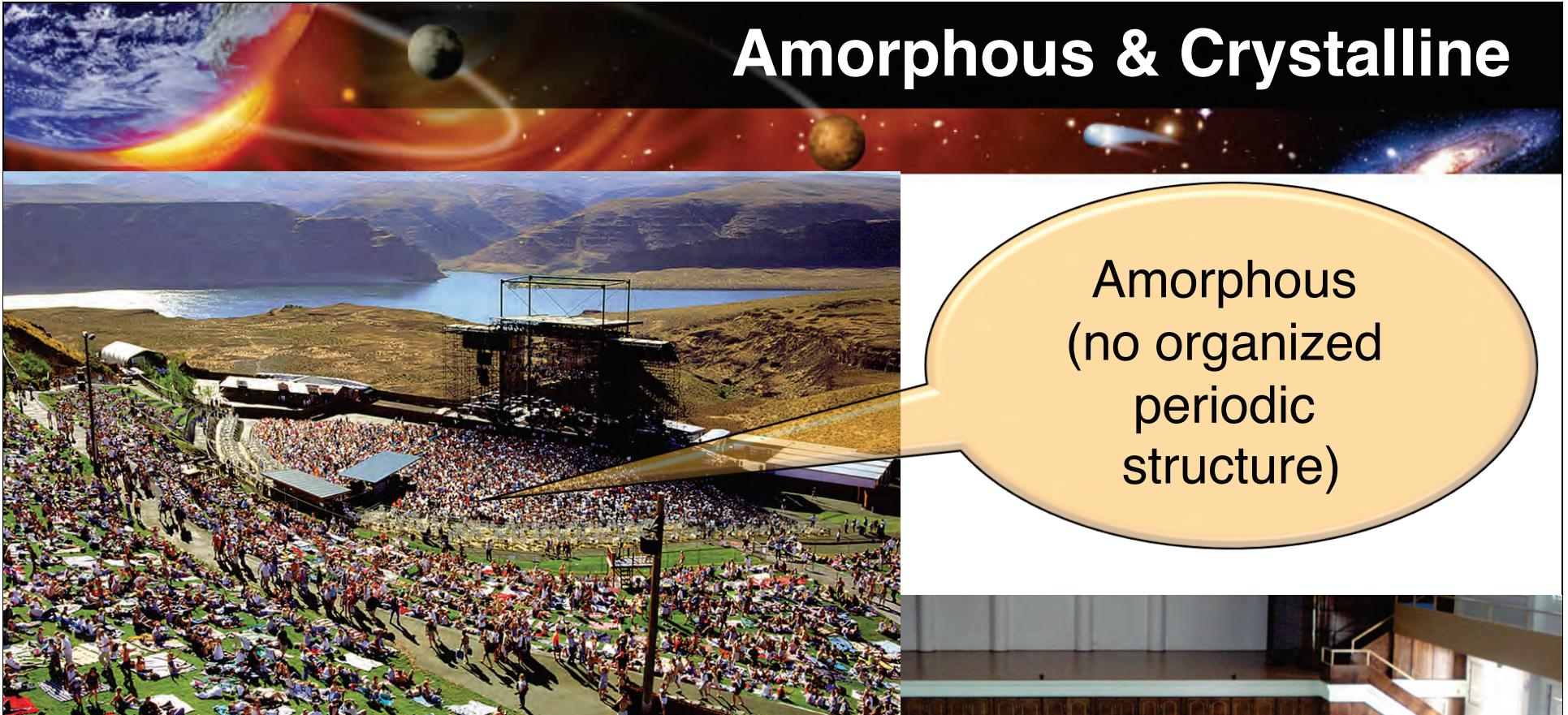


Amorphous or Crystalline?

Amorphous Ice

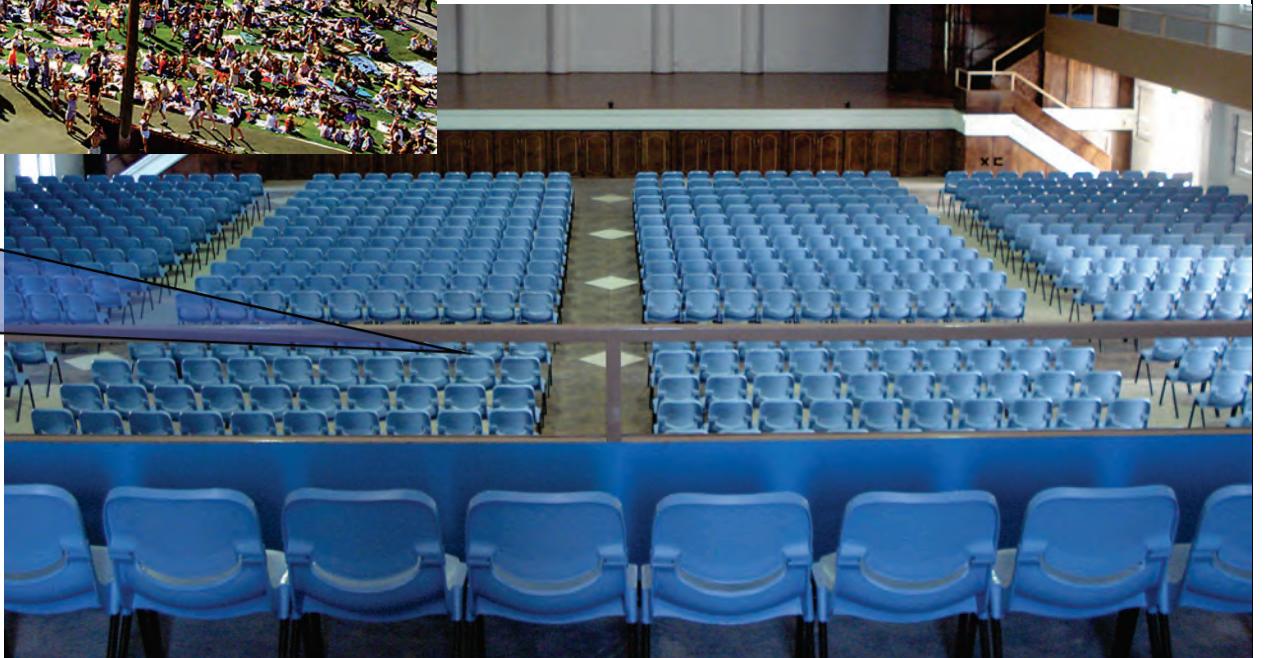
- ❖ Metastable Form
- ❖ Primarily Formed by H₂O Vapor Condensation below 120 K
- ❖ Change to Crystalline Ice at Higher Temperature
- ❖ Highly Porous (Low Density) – More Room for Chemistry
- ❖ Poor Heat Conductor – Acts like Thermal Insulator

Amorphous & Crystalline



Amorphous
(no organized
periodic
structure)

Crystalline
(periodic, ordered,
compact
structure)





Crystalline Ice



Crystalline Ice
(Polycrystalline)
Non-Transparent
Non-Compact
Light (Lower Density)



Crystalline Ice (Single Crystal)
Transparent
Compact
Heavy (High Density)



Polycrystalline vs. Amorphous Ices



Polycrystalline Ice
Non-Transparent
Non-Compact
Light (Lower Density)



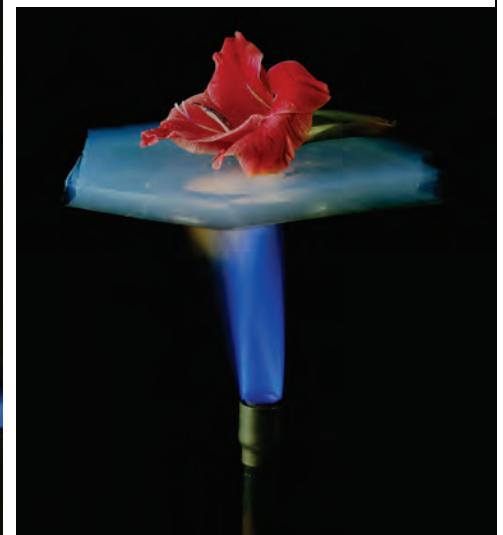
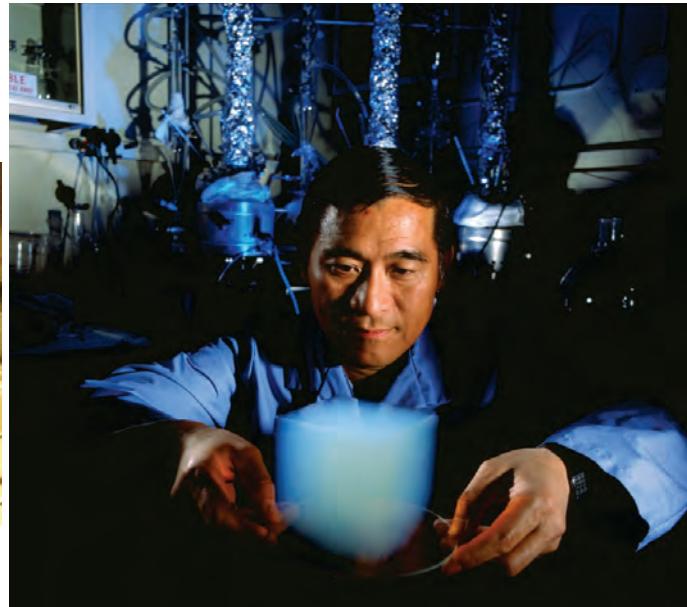
Amorphous Ice
(Cotton Candy Like)
Non-Transparent
Non-Compact
Light (Lower Density)

Amorphous Ices - Poor Heat Conductors

Amorphous ices conduct heat 1000 – 10000 times LESS efficiently than the crystalline ices. Rock and crystalline ice are similar in their thermal conductivity!

Amorphous ices are like wood, plastic, or aerogel.
All are poor heat conductors and protect interior
from outside heat.

Wood and plastic are poor heat conductor - everyday kitchen experience



Silica Aerogel (poor heat conductor) protects flower from the heat of the flame

Peter Tsou (Pathfinder & Stardust)



Subsurface Ice

- ◆ Why icy surfaces of cold icy bodies are significantly crystalline?
- ◆ Is the bulk ice of comets, KBOs, Oort Cloud bodies amorphous or crystalline?
- ◆ How about the near sub-surface of Saturn's icy moons (<100 K) – amorphous or crystalline? Saturn's rings?

Answers to these questions will determine how these bodies in the outer solar system evolve and how they are connected to the interstellar medium that dates before the birth of a star.

Amorphous Ices Protect the Interior

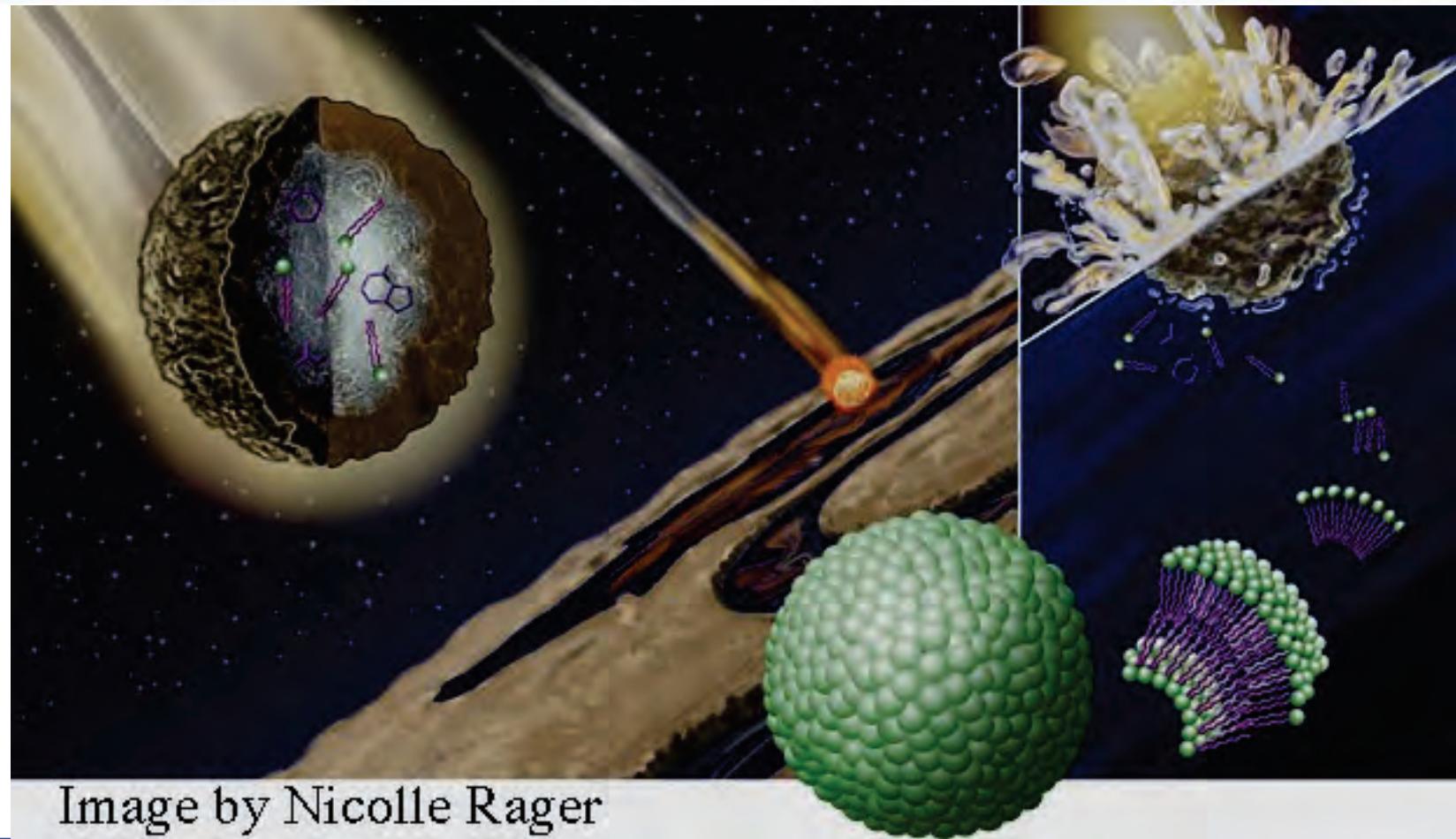
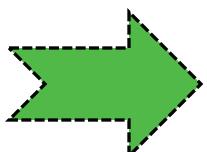


Image by Nicolle Rager

Amorphous comet ice bulk (poor heat conduction) better for protecting the fragile building blocks of life in the interior.



- **Ice: Definition**
- **Ice: Source of Water and Life? - Motivation**
- **Ice Spectroscopy Lab (ISL) @ JPL**
- **New Science Results from ISL**
- **Implications**
- **Some outstanding issues**
- **Summary & Future**



Ices are all over the Universe

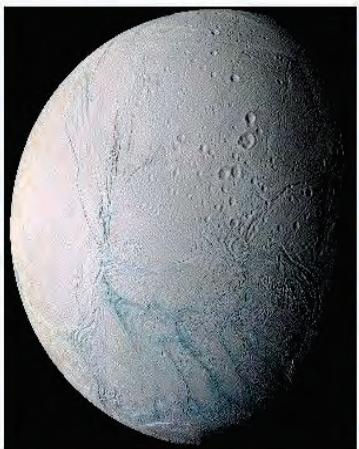
Earth Sciences



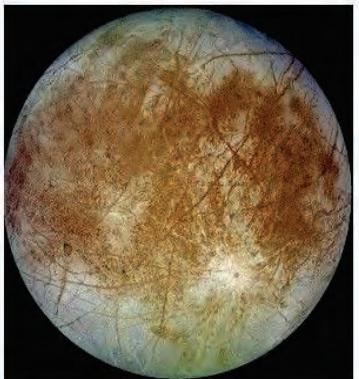
Atmospheric Aerosols



Polar (bear) ices

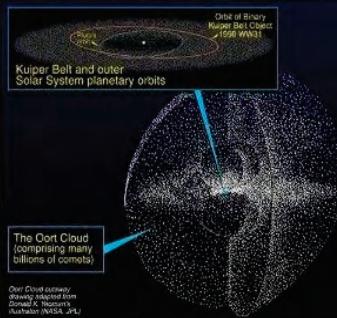
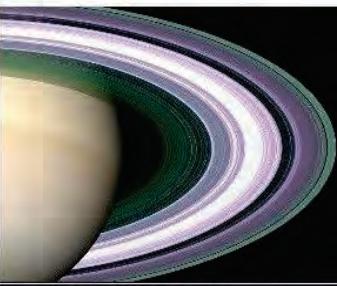


Enceladus



Europa

Planetary Sciences



Kuiper-Belt-Objects



Comets (Hale-Bopp)

Astrophysics



Galactic (Milky Way)
Interstellar Medium



Horse-Head Nebula
Dense Molecular Clouds



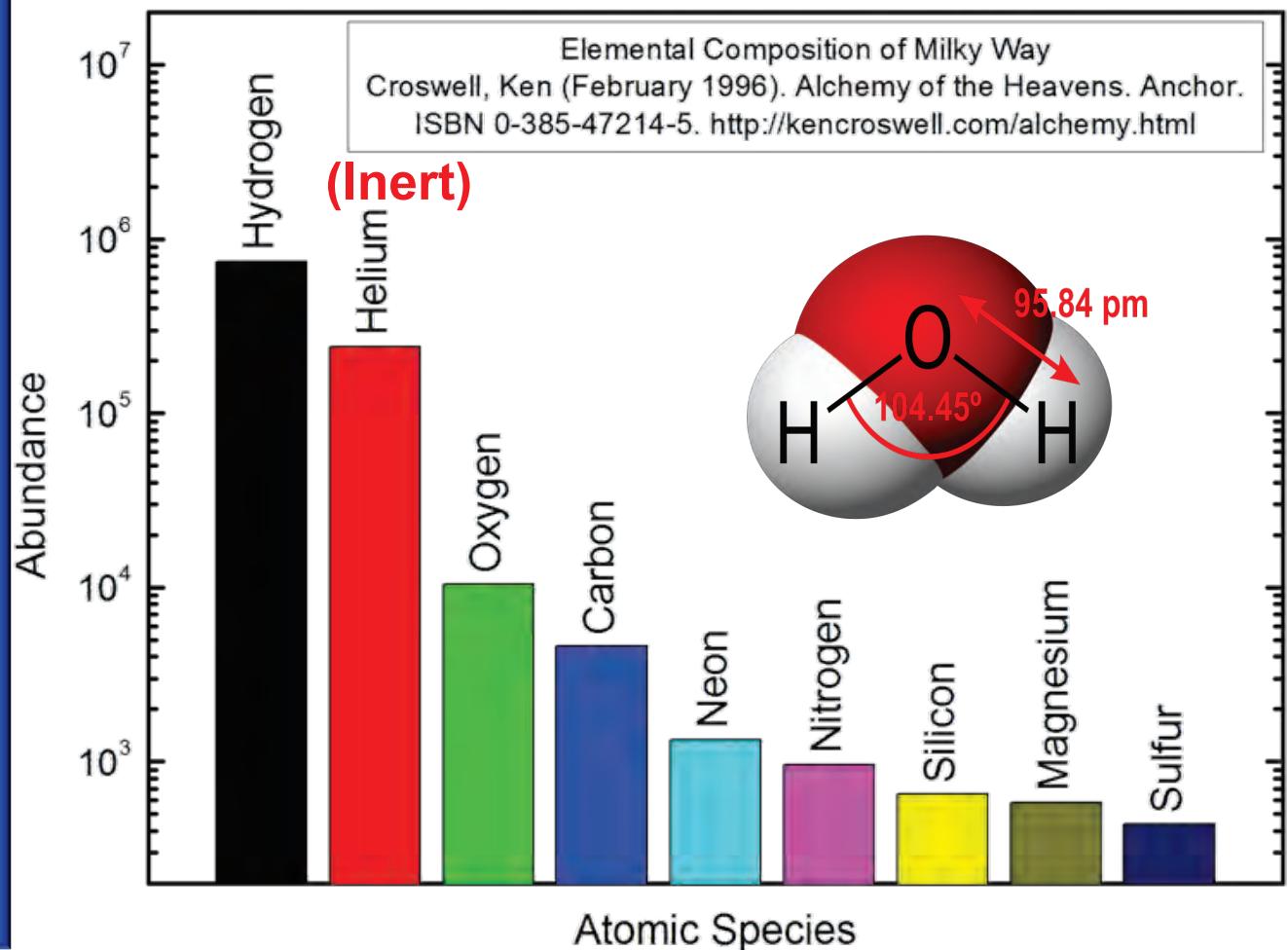
NGC-7331 Twin of the Milky Way

From Earth to Interstellar Medium Ices are Everywhere

Why Water Ice so Abundant?

Most abundant molecules in the Universe

H_2 (Hydrogen)
 H_3^+ (Trihydrogen)
 H_2O (Water)
 C_nH_m (Hydrocarbons)
 NH_3 (Ammonia);
 O_2 (Oxygen);
CO (Carbon Monoxide)
 CO_2 (Carbon Dioxide)
 N_2 (Nitrogen)
Etc...



H_2O is the most abundant triatomic molecule based on cosmic elemental abundance.

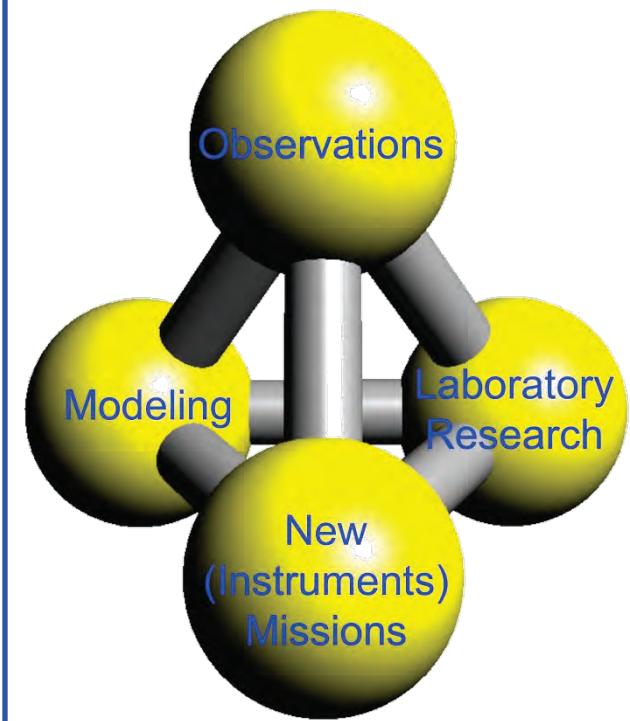


Take Home Message

- ✧ Ices are everywhere in the Universe
- ✧ Ices are not “passive and inert” mass that melt away – rather active participants in the evolution of the Universe!
- ✧ Comet ices could have brought life ingredients to Earth.
- ✧ Icy places may potentially be habitable (life elsewhere).
- ✧ Amorphous ices – odd, but important – connecting interstellar matter and evolution of solar systems.
- ✧ Charging ices could occur easily through Sun’s UV light – catalyzing cloud formation.
- ✧ Laboratory research is a critical and integral part of Space Science Endeavor!

Future: Ice Science Questions

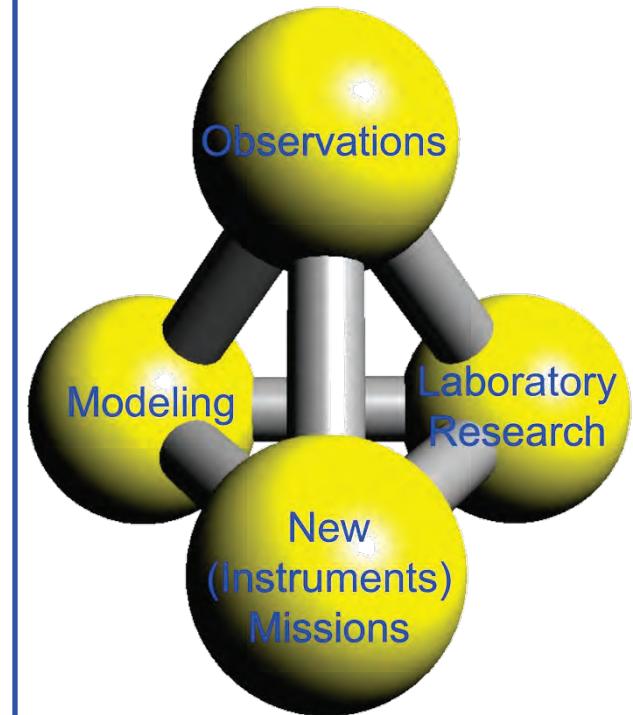
- ❖ Composition of cloud and surface ice on Earth: Can organic pollutants cause significant changes in surface snow mass and cloud ice photochemistry on Earth?
- ❖ Organics in Ice (Life) on Mars: Where are organics on Mars? Mineral/Ice surface or subsurface? How deep?
- ❖ Amorphous vs. Crystalline Outer Solar System: Is there amorphous ice in icy bodies beyond Jupiter? What are comets made of? How do the interiors of these bodies look like?
- ❖ How Thick is Crystalline Ice Surface: Observation of crystalline surface ice in the outer solar system – how thick? Millimeters or meters?
- ❖ Interior Ices: Transport of material and energy through high-pressure crystalline ice interior – what are the pathways?



Future: Ice Mission Focus

In-Situ (at the site) is the Future Mission: In-situ surface and subsurface ice probing is the ultimate solution to understand the evolution of ices and organics in our solar system.

- ❖ Spectral Imaging of Earth's Ice Ecosystem (UV -to- IR);
- ❖ Earth's Ice Composition and Chemistry;
- ❖ Mars Ice Drilling;
- ❖ Comet Sample Return (<50 K);
- ❖ Europa Surface Probe;
- ❖ Titan Surface Probe;
- ❖ Source of Enceladus Plumes;
- ❖ Composition of Saturn's Rings;
- ❖ Multiwavelength Spectroscopy of Interstellar Ices;
- ❖ etc...



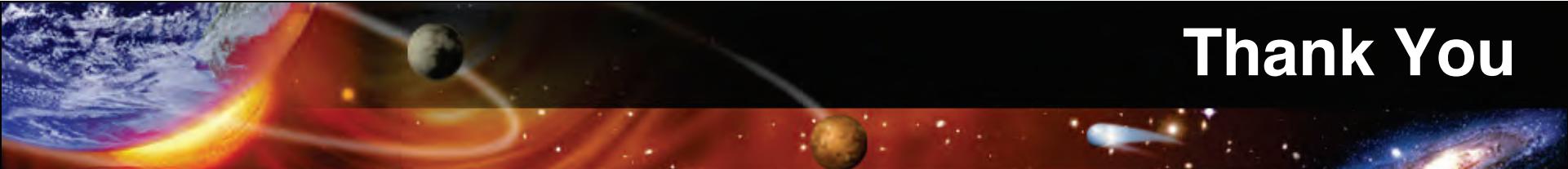
Laboratory Research

Laboratory data on many fronts is still missing and needs to be conducted, compiled and coordinated.

Today's laboratory research – tomorrow's space instrumentation!

Acknowledge the Funding from :

- Generous Start-up Package and Strong Support from JPL
- JPL's DRDF and RTD Funds
- NASA Planetary Atmospheres
- NASA Planetary Geology and Geophysics
- NASA Cassini Data Analysis
- NASA Discovery Data Analysis
- NASA Astrobiology Institutes: Icy Worlds (JPL), Titan (JPL), and Early Habitability (NASA Ames)



Thank You

**We came a long way!
But there is more out there!**



Himalayan Range